EVALUATION OF SUSPENDED SEDIMENT FLUX ALONG A CROSS-SECTION OF THE BRAHMAPUTRA RIVER

A thesis submitted to

The Indian Institute of Technology Guwahati

For the award of the degree of

DOCTOR OF PHILOSOPHY

By

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February 2013

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CERTIFICATE

This is to certify that the thesis entitled "**Evaluation of Suspended Sediment Flux along a Cross-Section of the Brahmaputra River**", submitted by Bhupendra Barman (Registration No. 004401), contains the findings of independent research work carried out by the researchers himself. The entire research work and the thesis have been built up under my supervision. The matter contained in this thesis has not been submitted elsewhere for the award of any other degree.

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ABSTRACT

In the present study, sediment samples (bed sediments and suspended sediments in the top 1 m surface water layer referred here as 'TWLSS'- Top Water Layer Suspended Sediments) were collected from the Brahmaputra River to investigate their characteristics. Moreover, water discharge (Q) data (15th May 2001 to 15th October 2008) and depth-integrated suspended sediment concentration (C) data (1st December 2003 to 15th October 2008) collected from Central Water Commission (CWC), Middle Brahmaputra Division, Government of India, were used to examine various trends in the data, C-Q relationships, and estimate total sediment load.

Annual sediment loads of the Brahmaputra River was in the range of 259 to 483 million tons/yr (445 to 832 tons km^{-2}.yr^{-1}) at the sampling sites, out of which fine (< 75 µm), medium (75-200 µm) and coarse (>200 µm) fractions constituted 86-194 (43.2 %), 83-154 (36.3 %) and 60-71 (20.5 %) million tons/yr respectively. About 65% of the total annual water discharge occurred during the monsoon months (June to September), which usually experiences 65-80% of the average annual rainfall. More than 80% of the total annual sediment load was found to be transported in the monsoon months while very low amount (~ 2 %) is transported in the winter months and the rest during the remaining months.

Suspended sediment concentration (C) was found to increase with discharge (Q). C-Q relations exhibited usually Figure-eight form of hysteresis, indicating contribution of sediments from both nearby and distant sources. Similar pattern of C-Q relation was exhibited at Bahadurabad (Bangladesh) by Coleman's (1969) data, indicating possibility of such sediment-discharge relationship to be true at other locations of the river as well.

Concentrations of TWLSS during monsoon months showed increasing trends towards the south (left) bank of the river indicating possible partial mixing of the inputs from a tributary joining the river at about two km upstream of the sampling site.

Both TWLSS and bed sediments were mesokurtic, normally distributed and poorly sorted. TWLSS particle sizes were occasionally polymodal and gap-graded indicating sediment contributions from diverse sources. Grain sizes of TWLSS and bed sediments fell mostly in 1 to 100 µm and 1 to 1000 µm ranges respectively, while ~ 82% of bed sediments belonged to 1 to 100 µm size. Average clay contents in TWLSS and bed sediments were about 8.9 % and 4.7 % respectively. Silt was the dominant fraction in both TWLSS and bed sediments. Specific surface area and TWLSS concentration were found to be negatively correlated ($p = 0.02$).

Particle shapes of both TWLSS and bed sediment were mostly oblate, prolate or bladed with sharp edges, suggesting their textural immaturity. Surface textures also revealed angular outlines, fractured blocks, conchoidal breakage, parallel and sub-parallel steps and even surfaces. Dissolution pits and hollows, secondary growth and surface etching visible on the sediment particles could be attributed to the chemical activities undergone by them.

The suspended sediment transport in the Brahmaputra River was found to be controlled by flow hydraulics at lower discharges and by supply at higher discharges. This explains the formation of Figure-Eight form of hysteresis in C-Q relationship. Since major fraction (> 80%) of the annual sediment load was found to be transported during the monsoon months characterized by higher discharges, suspended sediment in the Brahmaputra River appears to be mostly supply controlled.

Cumulative frequency distribution curves for TWLSS grain sizes and Coarsest Percentile-Median (C-M) diagram revealed either absence of a graded suspension or presence of a thin layer of it at the present study site. Dominance of silts in the sediments points to the existence of a uniform suspension at the study site.

Order of mineral abundance in TWLSS was as Quartz > Albite > Illite > Kaolinite > Muscovite > Orthoclase > Chlorite > Montmorillonite, and in bed sediment as Quartz > Albite > Kaolinite > Illite > Chlorite. Detrital minerals (quartz, feldspar and mica) constituted about 80% of the total minerals present in the sediments, quartz alone being about 67%. Among feldspars, albite was predominant. Illite, kaolinite and chlorite formed more than 85% of the total clay minerals. Illite and kaolinite were the major clay minerals. Presence of montmorillonite in most of the sediment samples suggested chemical transformation of aluminosilicates during sediment transport, and / or contribution from volcanic rocks present in the upper drainage basin of the Brahmaputra River. High values of Q:F (Quartz : Feldspar) and Q:M (Quartz : Mica) indicated loss of feldspar and mica due to chemical weathering. Low mica contents might also be due to the geochemical environments and / or geology of the basin.

Abundance (wt %) of major elements in the TWLSS was as O > Si > Al > Fe > K > Mg > Ca > Na > Cu > Ti and in bed sediments as O > Si > Fe > Al > K > Mg > Ca > Na > Ti. Both TWLSS and bed sediments were depleted in Na and Ca, and enriched in Fe, Si and K compared to Earth Crust compositions, indicating prevalence of chemical weathering in the basin. Enrichment of TWLSS in Al might be due to higher amount of clay minerals compared to that in the Earth Crust. Fe enrichment in the sediments points to presence of primary ferromagnesian silicates or Fe-rich secondary phases in the basin. Degradation of mica and other K-silicate minerals might have enriched sediments in K.

Abundance of trace metals (µg / g) in the TWLSS was as Al > Fe > Mn > Zn > Ni > Pb > Cu > Cr > Cd and in bed sediment as Al > Fe > Mn > Zn > Ni > Cu > Cr > Pb > Cd. Almost all the metals showed enrichment in TWLSS over bed sediments. The enrichment factors for various metals were as follows: Zn (4.13), Pb (2.13), Cd (2.02), Al (1.70), Ni (1.26), Mn (1.17), Fe (1.07), and Cr (1.01).

The Brahmaputra River was found to be in an uncontaminated status in terms of trace metal concentrations. In the sediments, concentraons of metals decreased with clay content but increased with silt content. Since silt was the dominant fraction of the sediments and river water was alikaline, metal transport in the Brahmaputra River occurred mainly by adsorption to silt.

From the findings, it can be concluded that the high volume of sediment carried by the river Brahmaputra can be characterized by their specific textural, mineralogical and compositional properties. These properties currently prevalent in the relatively pristine state of the river can be used as guidelines for evaluating future changes in sediment profile when the river will be subjected to gradually increasing human impact. Since only sporadic studies with only one or two sample are available from the past for the study area, any further study on the evolution of the suspended load can consider the present study as a benchmark.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervisor Dr. Chandan Mahanta for his guidance, encouragement and gracious support throughout the course of my work, for his expertise in the field that motivated me to work in this area and for his faith in me at every stage of this project. He has patiently listened to numerous ideas, good and bad, and questions I have had and he has given me extremely useful and incisive comments in return. I look forward to continue working with him and further developing our relationship. I hope that I can live up to his high standards.

Besides my supervisor, I would like to express my wholehearted gratefulness to Dr. Pinakeswar Mahanta, Dr. Gautam Barua, and Dr. Arup Kr. Sarma, the other members of my doctoral committee, for their advice, suggestions and encouragement during the course of this research.

I am thankful to all in the Civil Engineering Department, Indian Institute of Technology Guwahati, for providing me with the facilities needed for completion of my project.

I am grateful to Dr. Utpal Bora, Dr. B. K. Patel, Dr. A. Chattopadhyay and all other faculties of the institute who encouraged me to keep up my spirit to endure the rigour of research work.

I will remain always grateful to my colleagues and sirs who directly or indirectly helped me to acquire this achievement, particularly those associated with granting me permission and leave for doing PhD at this renowned institute.

Many people supported me during the completion of this thesis with helpful criticism, assistance and references. A few of them are Dr. C. R. Deka, Keshab, Partha, Koustav, Kula, Jonali, Payodhar, Wazir, Manash, Pranjal, Vikash, Vishal, Kushal, Bimal Da, Prabir Da.

I am grateful to those officials of Central Water Commission (CWC), Middle Brahmaputra Division, Government of India, who helped me to get some of their data on the Brahmaputra River used in this thesis.

I owe a debt of thanks to the authors whose books or articles are listed in the references. Many of the ideas and examples in this book stemmed from those sources.

I am immensely grateful to “Dada” (Srijut C.M. Patowary) and ‘Bou” (Dr. Rita Choudhury) for their help and encouragement for doing this research work.

I have to acknowledge and present my heartfelt appreciation to my wife (Hima) for all the encouragement and support throughout this tough time, which made the completion of this work possible, and express my gratefulness to her for listening to my complaints and frustrations, and for believing in me all the time. Special thanks are due to my sons, Paul (Nidarshan) and Riddhi (Abhijnan), for their lovely spirits which swept away my stress in the course of this work. This achievement would have been impossible without my mother’s blessings.

Above all, I stand where I am because of the grace and mercy showered on me by the Lord.

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NOTATIONS

C: Sediment Concentration

d_I: Intermediate grain axis

d_L: Longest grain axis

d_S: Shortest grain axis

D: Inclusive graphic standard deviation

D[3,2]: Surface weighted mean diameter

D[4,3]: Volume weighted mean diameter

d_x: Grain size at which x% of the sample is finer than that size

K: Kurtosis

M: Graphic mean

Q: Discharge

S: Skewness

Φ_x: Grain size at which x% of the sample is coarser than that size

ABBREVIATIONS

A:	Albite
AAS:	Atomic Absorption Spectrophotometer
ASTM:	American Society for Testing and Materials
C:	Chlorite
CEC:	Cation Exchange Capacity
COV:	Coefficient of Variation
CWC:	Central Water Commission
DNA:	Deoxyribonucleic acid
DO:	Dissolved Oxygen
EPA:	Environmental Protection Agency
EDS:	Energy Dispersive X-Ray Spectroscopy
EPS:	Extracellular Polymeric Substance
GBM:	Ganga-Brahmaputra-Meghna
I:	Illite
ISC:	Inner Sphere Complexes
JCPDS:	Joint Committee on Powder Diffraction Standards
K:	Kaolinite
M:	Montmorillonite
Mu:	Muscovite
O:	Orthoclase
OSC:	Outer Sphere Complexes
PDF:	Powder Diffraction File

PSA:	Particle Size Analysis
PSD:	Particle Size Distribution
PZC:	Point of Zero Charge
PZNPC:	Point of Zero Net Proton Charge
Q:	Quartz
RAV:	Relative Atomic Variation
SD:	Standard Deviation
SEM:	Scanning Electron Microscope
SOP:	Standard Operating Procedure
SSC:	Suspended Sediment Concentration
TOC:	Total Organic Carbon
TWLSS:	Top Water Layer Suspended Sediment
WAPCOS:	Water and Power Consultancy Services (India) Limited

CHAPTER 1

INTRODUCTION

1. Introduction

Sediment is defined as particles derived from rocks, biological materials, or chemical precipitants, which are transported by, suspended in, or deposited by flowing water. Suspended sediment is that part of sediment which is carried in suspension by the turbulent components of the fluid or by Brownian movement (ASTM, D 4410-03).

1.1. Sediment generation processes

Sediment is formed as a by-product of weathering and erosion. Disintegration and decomposition of rocks occur during weathering by natural physical (e.g., large diurnal temperature shifts, salt wedging, frost wedging) and chemical (e.g., hydrolysis and hydration reactions, oxidation, leaching and volatilization) processes. Movement of weathered products may be described by the following equations:

$$\text{Weathering + Gravity} \longrightarrow \text{Mass wasting}$$

$$\text{Weathering + Gravity +Moving fluid} \longrightarrow \text{Erosion}$$

1.1.1. Erosion and sediment transport

Ellison (1946) has defined soil (final product of weathering) erosion as a process of detachment and transportation of soil materials by erosive agents. The most important force of erosion is gravity and the most important agent of erosion is water. Wind and glaciers are other erosive agents. Erosion converts soil into sediment.

Erosion will take place on the surface when the force provided by the flow (runoff) exceeds the resistance of the soil. Erodibility is a function of rainfall intensity, permeability of the surface, chemical and physical properties that control the disintegration of the rocks and the cohesiveness of the soil, and the vegetation, which directly affects both the stability and the infiltration capacity of the soil (Leopold et al, 1964).

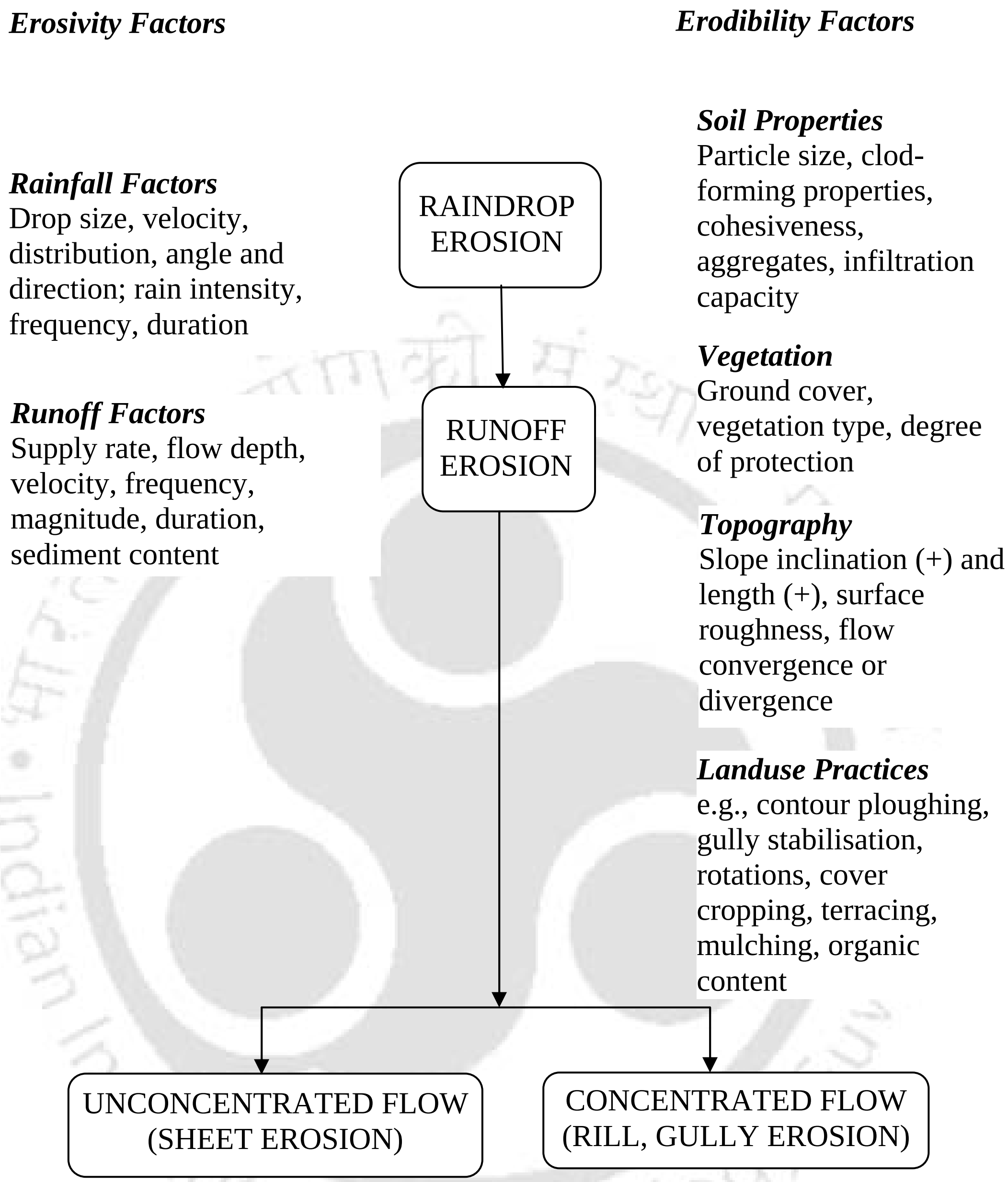


Figure 1.1: Summary of principal factors controlling water erosion on hillslopes and sediment yield to river channels (Charlton, 2008; cited from Cook and Doornkamp, 1990)

Impact of raindrop is a primary cause of surface erosion. Raindrop size, distribution, fall velocities, and total mass of impact determine its erosive potential. At first, rain water undergoes infiltration. After the ground becomes saturated, the rain drops begin moving across the landscape above the surface. This is called overland flow.

Recorded velocities for overland flow are commonly in the range of 0.015 to 0.3 m/s which is great enough to move silts and sands (Selby, 1993). This flow carries small amounts of dust and dirt with it. This is called splash erosion. The sheet of moving water becomes larger with rain and forms rills (small channels) by detachment of soils. Absence of vegetation accelerates formation of rills. Eventually many rills combine to form gullies. Gullies may yield tremendous volume of sediment by large concentration of runoff which is fed into streams and rivers. Not all eroded materials from a watershed reach a stream system. The ratio of sediment delivered at a given location in the stream system to the gross erosion from the drainage area above that location is the sediment delivery ratio for that drainage area.

Streams and rivers possess tremendous amount of force and so can cause a great amount of erosion in terms of stream bank erosion, degradation and floodplain scour.

1.2. Sediment sources

Sources of sediments include upland areas, stream banks or stream or river channels. Sheet, rill and gully erosion from agricultural lands is often cited as a primary source of sediments in aquatic receiving systems. However, other sediment sources such as mining, forestry and especially urban development contribute greatly to the influx of sediments into aquatic receiving systems. The quantities of materials contributed by headland erosion and aeolian transport are both less than 2% of river transport (Sarma, 2005). Virtually all suspended matter is supplied by terrestrial erosion (runoff, mass flows, ice flows, and aeolian supply) or through the production of organic matter, biogenic carbonate, and biogenic opal, along with the sediments originated from weathering of mineral and soil upstream and susceptible to transport downstream by the river water (Borah, 2006).

1.3. Controlling factors for sediment yield

Runoff intensity, steepness of morphology (relief), precipitation and lithology are major factors which control sediment yield (Ludwig and Probst, 1998). Soil protection by vegetation cover reduces mechanical erosion and consequently, sediment yield. Vegetation cover protects the surface from raindrop impact, controls the infiltration rate, and reduces surface runoff (Thornes, 2001). Hence, dense surface vegetation cover decreases soil erosion risks (Snelder and Bryan, 1995). Molina et. al. (2008) found vegetation cover and lithology to be highly correlated with sediment yield (catchment area underlain by argillaceous rocks). Natural disturbance events like climate change, tectonic uplift, forest fires and volcanic eruptions affect sediment yields by modifying these controlling factors. Anthropogenic disturbances, such as channelisation, damming and dredging, also affect sediment yield.

Heavy precipitation, steep hill slopes, friable nature of rocks, deforestation, and shifting cultivation in the catchment areas are some factors for large quantity of sediment in the Brahmaputra River. Earthquakes can cause inflow of enormous quantity of sediment into a river rather abruptly as happened after the earthquakes of 1947 and 1950 in Assam (As cited by Borah, 2006, from Master Plan of Brahmaputra Basin, Part-I, Main Stream, 1986).

According to Sharma (2002), basin area is a significant controlling factor of sediment yield. He observed the following relations between annual sediment yield (S_y, in tonnes) and basin area (A, in square kilometer): $S_y = 1260A^{0.63}$ for South Asian region; $S_y = 6310A^{0.83}$ for the Hindukush-Himalayan region; and $S_y = 930A^{0.95}$ for the South and Central region of the Indian subcontinent. Some examples of retention of transported sediment by river basins are as follows: 65% in the Mahanadi River Basin (Chakrapani and Subramanian, 1990), 70% in the Brahmaputra River Basin (Goswami, 1985) and

57% in the Indus River Basin (Ahmad and Choudhary, 1988). Table 1.1 shows annual transport of sediment from the continent to the oceans.

Table 1.1: Transport of sedimentary material from continent to oceans (Edwards, 2007)

Continent	Land Area (10^6 km^2)	Mean annual runoff (10^3 km^3)	Total annual suspended sediment load (10^6 t yr^{-1})
Africa	15.3	3.4	530
Asia	28.1	12.2	6433
Europe	4.6	2.8	230
North and Central America	17.5	7.8	1462
Ocenia and Pacific Islands	5.2	2.4	3062
South America	17.9	11	1788

1.4. Classification of sediments

In terms of initial supply of sediments into a sedimentary system, three basic sediment types can be delineated. These are: (i) detrital minerals, (ii) biogenic or organic sediments and (iii) anthropogenic particles and compounds (Perry and Taylor, 2007).

Detrital minerals are released by weathering of rocks. Many terrestrial and marine sediments contain detrital minerals like quartz and feldspar as a primary component. Remains of skeletal carbonate-secreting organisms (coral reef) and organic inputs derived from plant materials (salt marshes, mangroves) give rise to biogenic sediments. Building and industrial materials, vehicle wear, combustion particles are sources of anthropogenic-sediments grains. Contaminants (metals, radionuclides, etc.) are significant components of modern sediments.

Transported fluvial sediment can be classified as either bed load or suspended load. Bed load consists of coarse sediment (>0.0625 mm) carried along the river bottom and suspended load is the finer sediment (<0.0625 mm) moved in suspension. About 90%

of the sediment of a river is carried in suspension. The amount of suspended load increases during floods due to increased stream power.

1.5. Sediment properties:

1.5.1. Physical properties

Size, shape and density are some important physical properties of sediment. Fine grained sediments may sometimes form flocs whose properties (settling, transport, sorption, etc.) are significantly different from those of individual grains.

1.5.1.1. Size

Grain size is an important parameter for describing sedimentary particles and for understanding sediment transport and deposition. As the grain sizes of sediments vary over wide range, sediments are grouped into different size classes or groups (Table 1.2).

Table 1.2: Wentworth scale of grain size

Diameter	**Type**
>256 mm	Boulder
64-256 mm	Cobble
32-64 mm	Very coarse gravel
16-32 mm	Coarse gravel
8-16 mm	Medium gravel
4-8 mm	Fine gravel
2-4 mm	Very fine gravel
1-2 mm	Very coarse sand
0.5-1 mm	Coarse sand
0.25-0.5 mm	Medium sand
125-250 μm	Fine sand
62.5-125 μm	Very fine sand
3.9-62.5 μm	Silt
<3.9 μm	Clay
<1 μm	Colloid

Size distribution of sediments is influenced by energy in the system (wind, waves or current) and its variability, distance from source of sediments, and size/shape of sediments.

Since particle diameter typically span many orders of magnitude for natural sediments, base two logarithmic (φ, phi) scale is used for easy comparison among various sediments and it is defined as

$$\Phi = -\log_2 D$$

where φ = particle size in φ units and D = diameter of particle in mm. Some important statistical parameters of grain size (phi scale) are graphic mean (M), inclusive graphic standard deviation (D), skewness (S) and kurtosis (K). Meanings of these parameters for different values have been shown in Tables 1.3 A, B, C.

Table 1.3 (A, B, C): Some important statistical parameters and their significances

(A)

Graphic Mean (M)		**Inclusive graphic standard deviation (D)**	
Values	**Sediment type**	**Values**	**Degree of sorting**
< -1	Gravel	0 to 0.35	Very well sorted
-1 to 0	very coarse sand	0.35 to 0.50	Well sorted
0 to 1	coarse sand	0.50 to 0.71	Moderately well sorted
1 to 2	medium sand	0.71 to 1.00	Moderately sorted
2 to 3	fine sand	1.00 to 2.00	Poorly sorted
3 to 4	very fine sand	2.00 to 4.00	Very poorly sorted
4 to 8	Silt	> 4.00	Extremely poorly sorted
> 8	Clay		

(B)

Inclusive graphic standard Skewness (S)		
Values	**Mathematically**	**Graphically skewed to the**
1.00 to 0.30	Strongly positive skewed	Very Negative phi values, coarse
0.30 to 0.10	Positive skewed	Negative phi values
0.10 to -0.10	Near symmetrical	Symmetrical
-0.10 to -0.30	Negative skewed	Positive phi values
-0.30 to -1.00	Strongly negative skewed	Very Positive phi values, fine

(C)

Graphic Kurtosis (K)	
Values	**Verbal description**
0.41 to 0.67	very platykurtic
0.67 to 0.90	platykurtic
0.90 to 1.10	mesokurtic
1.10 to 1.50	leptokurtic
1.50 to 3.00	very leptokurtic
> 3.00	extremely leptokurtic

The formulae for these parameters are furnished below (Folk and Ward, 1957):

$$M = (\varphi_{16} + \varphi_{50} + \varphi_{84})/3$$

$$D = (\varphi_{84} - \varphi_{16})/4 + (\varphi_{95} - \varphi_{5})/6.6$$

$$S = [(\varphi_{84} + \varphi_{16} - 2 \text{ x } \varphi_{50}) / 2 \text{ x } (\varphi_{84} - \varphi_{16})] + [(\varphi_{95} + \varphi_{5} - 2 \text{ x } \varphi_{50}) / 2 \text{ x } (\varphi_{95} - \varphi_{5})]$$

$$K = (\varphi_{95} - \varphi_{5}) / [2.44 \text{ x } (\varphi_{75} - \varphi_{25})]$$

where φ_x refers to the grain size at which x% of the sample is coarser than that size. Standard deviation is a measure of the degree of sorting, skewness is the degree of asymmetry of a frequency or cumulative curve and kurtosis is the degree of peakedness of the grain size curve.

1.5.1.2. Shapes

Sediment particles are almost always irregularly shaped. The shape is described by its form, roundness and texture. Roundness is a measure of smoothness of the corners of a sediment particle. Roundness of a grain is defined as the ratio of the average radius of curvature of individual edges to the radius of the largest circle that can be inscribed within either the projected area or a cross section of the grain. Roundness is usually described on the basis of visual identification charts. Form is described as oblate (disc, tabular), equant (spherical), bladed or prolate (roller, rod-like) on the basis of the ratio between the short (d_S), intermediate (d_I) and longest (d_L) grain axes (Figure 1.2). The shape of a sediment particle is described by shape factor [=c/√(ab)] where a, b and c are respectively the longest, intermediate and shortest of the mutually perpendicular axes of the particle. Most natural sand particles have a shape factor of about 0.7 (Boiten, 2008).

Particle sorting describes the range of grain sizes that occur within a sedimentary deposit. Sorting together with grain size data can help to infer information about the environments of sediment deposition and the history of sediment reworking (Perry and Taylor, 2007).

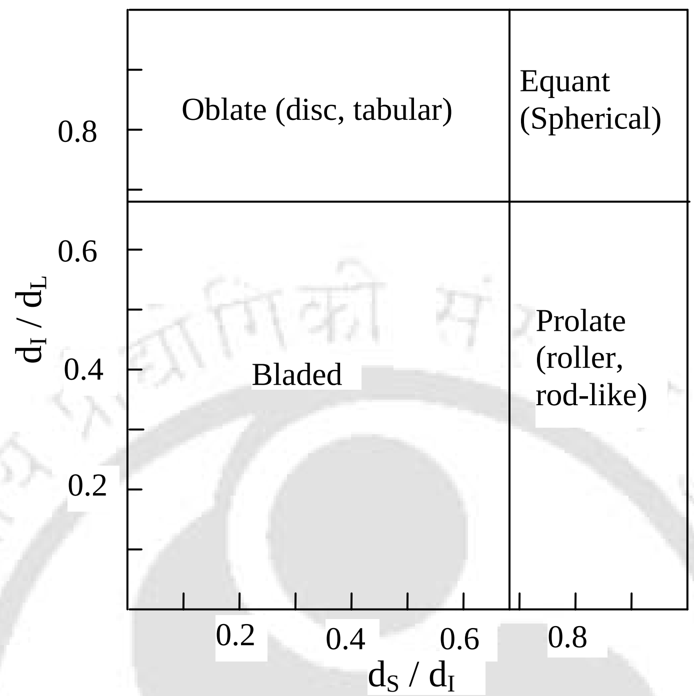


Figure 1.2: Classification scheme used to describe particle form based on the ratio between the shortest, intermediate and longest grain axes (Perry and Taylor, 2007)

1.5.2. Sediment composition

Sediment particles are primarily inorganic particles and are generally coated with metal oxides (of aluminium, iron and manganese), as well as viable (bacteria and phytoplankton) and nonviable (proteins, carbohydrates, lipids, and humic substances) organic substances. Most inorganic particles are silicate minerals that can be further subdivided into silica minerals (quartz and opaline silica); the clay minerals (usually kaolinite, illite, montmorillonite and chlorite); and other silicates (feldspars, zeolite) (Lick, 2009).

Most of the earth's crust is composed of only eight elements: oxygen (47% by weight), silicon (28%), aluminium (8%), iron (5%), calcium (4%), potassium (3%), sodium (3%) and magnesium (2%) (Williams, 2004). On a volume basis, the crust is composed almost entirely of oxygen, which are bonded to interstitial metal cations. Five classes of rocks occupy more than 90% of the continental area and the approximate proportions of common minerals exposed to weathering at the surface are shown in Table 1.4. The zone of weathering involves half a dozen major rock types, mostly 8-10 mineral groups and 8 chemical elements (Leopold et al., 1964). Sediment, being a product of weathering and erosion, will retain the relative abundance of initial mineralogical composition of the bedrock. But, numerous phases of weathering (mainly chemical weathering), transport, deposition, storage, lithification, reworking and redeposition, may significantly alter the original grain composition (Perry and Taylor, 2007).

Table 1.4: Major rock types and minerals exposed to weathering (Leopold et al., 1964)

Type of rock	Approximate distribution (%)	Mineral	Proportion exposed to weathering (Approx.) (%)
Shale	52	Feldspars	30
Sandstone	15	Quartz	28
Granite (and granodiorite)	15	Clay minerals and micas	18
Limestone (and dolomite)	7	Calcite and dolomite	9
Basalt	3	Iron oxide minerals	4
Others	8	Pyroxene and amphibole	1
		Others	10

Mineral particles resistant to weathering are found in suspended sediments and suspended matters in aquatic systems. A list of major minerals generally present in sediments are furnished in Table 1.5.

Table 1.5: Common minerals found in sediments (Borah, 2006)

Mineral	Composition
Quartz	SiO_2
Opal	$SiO_2.nH_2O$
Albite	$NaAlSi_3O_8$
Anorthite	$CaAl_2Si_3O_8$
Orthoclase	$KAlSi_3O_8$
Calcite	$CaCO_3$
Aragonite	$CaCO_3$

Muscovite	$KAl_2(AlSi_3O_{10})(F, OH)_2$
Biotite	$K (Fe, Mg)_3 AlSi_3 O_{10} (F, OH)_2$
Goethite	$FeO(OH)$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Chlorite	$(Fe, Mg, Al)_6(Si, Al)_4O_{10}(OH)_8$
Montmorillonite	$(Na, Ca)(Al, Mg)_6(Si_4O_{10})_3(OH)_6 - {}_nH_2O$
Illite	$(KH_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2(H_2O)]$

1.6. Sediments in fluvial environment

Particle hydrodynamics refers to the propensity of a particle to remain immobile or to become entrained if it is on the bed surface, and to remain in suspension or to cease movement if it is in motion. Hydrodynamics of non-cohesive sediments is governed by mechanical forces and the relevant properties are particle size, shape and specific gravity. In case of cohesive sediments, electrochemical forces are dominant and the governing properties are particle size, water chemistry and mineralogy of the sediment (As cited by Borah, 2006, from Ranjithan et al., 1993).

1.6.1. Entrainment of sediments

The relationship that exists between the velocity of fluid flow and the size (diameter) of sediment that the fluid can carry was demonstrated by Hjulstrom (1935). Entrainment of sediment by a fluid depends on density, viscosity and velocity of its flow. The critical shear velocity for sediment entrainment depends on the grain size, shape, particle density, sediment packing and grain imbrications.

Particles in 0.2-0.7 mm size ranges (sand grains) are easiest to entrain. Entrainment velocity increases with larger size particles because of their greater immersed weights. Particles smaller than 0.2 mm (fine sand to silt and clay) tend to be partly or wholly enclosed within the laminar sublayer during most flows. This as well as the cohesive forces between clay particles increase the force required to set them in motion (Charlton, 2008).

It is important to note that Hjulstrom carried out his experiments using well sorted bed sediments of a single size, which is not representative of the conditions of many channels. The arrangement of grains on the bed and the mixture of grain sizes significantly affect the entrainment of individual grains (Charlton, 2008).

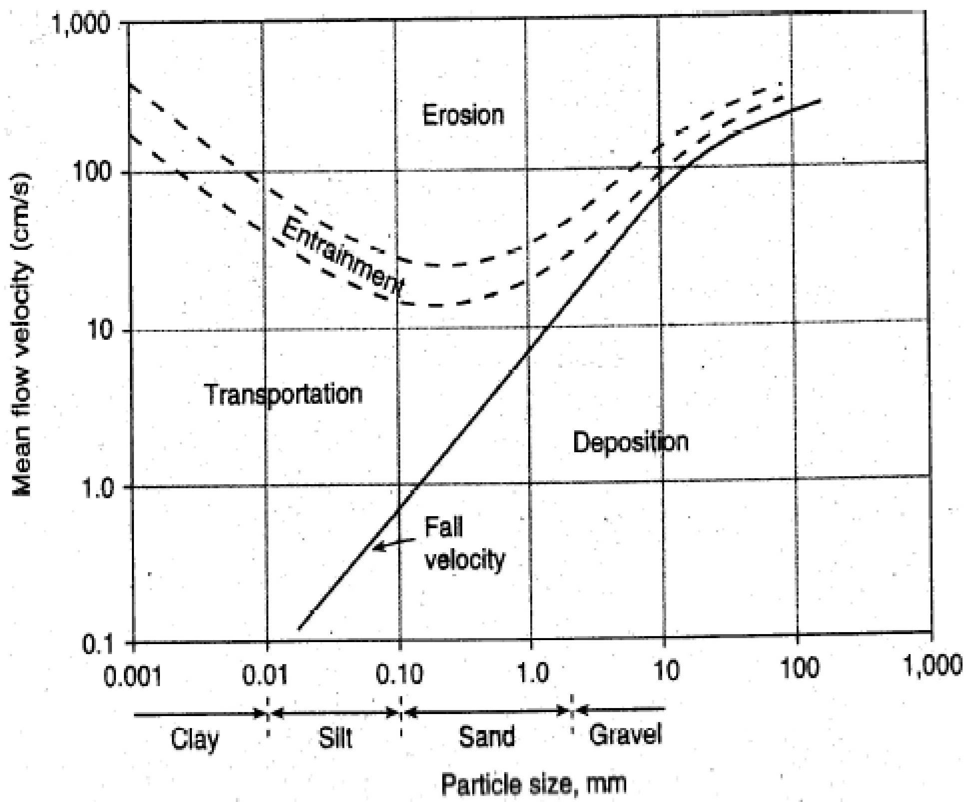


Figure 1.3: Hjulstrom's diagram (Source: Charlton, 2008)

1.6.2. Sediment transport

Once entrained, sediment movement occurs in three ways (Perry and Taylor, 2007):

- As bedload material that is too heavy to be lifted up into the water and moves by rolling along the substrate
- Via the process of saltation whereby lighter grains are temporarily lifted up into the fluid and then settle out

- In suspension where the lightest particles are held within the fluid and moved

An additional agent of sediment transport is gravity. Three main categories of gravitational transport are recognized: (i) rockfalls, (ii) slides and slumps, and (iii) mass flows. Rockfalls may be caused by tectonic movement or by weathering. The presence of water along a shear plane acts as a medium to initiate both slumping and sliding. At higher water contents, the process of slumping grades into mass flows. Unconsolidated sediment and steep slopes, low vegetation cover and heavy rainfall are necessary to initiate movement of the sediment.

1.6.3. Sediment transport as flocs

Majority of the sediments are transported as flocs (Droppo, 2001). Hence, transport of sediment-associated pollutants will depend upon the size, structure, composition and density characteristics of the flocs.

The key parameters for suspension and deposition behaviour of fine particles in rivers are flow turbulence, particle size distribution, particle surface charge, ionic strength, and the concentration of organic matter (Amos et al., 1992; Buffle and Leppard, 1995a, b). In rivers with low salt concentration, fine particles are stable in dispersion and remain mobile. An increase of ionic strength (e.g., in estuaries with mixing of river and sea water) enables particle aggregation and their sedimentation, resulting in accumulation and storage of sorbed contaminants in the river channel sediments (Frimmel et al., 2007).

Flocs consist of both organic and inorganic material, bound together by a combination of physical, chemical and biological forces (Droppo et al., 1997). Ionic and suspended sediment concentration, shear stress, pH, and organic source and supply influence the rate of flocculation (Droppo and Ongley, 1994). Flocs are prolific in marine environment. In freshwater lotic systems, these are normally an order of magnitude smaller than their marine counterparts (e.g. 10^2 to 10^3 μm diameter) (Petticrew et al., 2007).

Extracellular Polymeric Substance (EPS) consists mainly of polysaccharides and proteins, but can also contain substantial amount of DNA, lipids, glycolipids and humics. EPS may result from active secretion, shedding of cell surface material, cell lysis, and adsorption form the environment (Flemming et al., 2007). EPS are typically thought of as microbial structures actively developed by microbes for several key functions (Petticrew et al., 2007). Recent interdisciplinary studies on flocs support the idea that EPS composition is an important component whose surface properties control hydrophobicity and surface charge at the floc-water interface, while bound water can be a function of floc size and total EPS (Liao et al. 2001, 2002). These properties, as influenced by EPS, all play a role in the flocculation and contaminant interactions of cohesive sediments.

1.6.4. Vertical distribution of sediment in rivers

A vertical concentration profile, with lower values at the surface and higher ones near the bottom, of sediments occurs in rivers or streams due to gravity. Sediment is kept in suspension by the vertical component of turbulence in flowing water, which is of the order of 1% of the forward velocity. Random turbulent motion causes equal volumes of water to rise and to sink within the water column. As sediment concentration increases as a function of depth, the rising water column has a higher concentration than the sinking water, creating a net upward movement of sediment which offsets sedimentation and produces the vertical concentration gradient.

In most streams, the turbulent component is large compared to the sedimentation rate of silts and clays. The fines are typically transported as wash load, and the concentration of the sediment particles along a vertical within the water column is nearly uniform. In contrast, rapidly sinking sands normally has a concentration profile that tends to vary logarithmically as a function of depth. The concentration profile varies as a function of grain size, with large diameter particles being concentrated closer to the bottom of the vertical profile. The transport rate at any depth is a product of the velocity and concentration at that depth, and the total sediment load is the product of the mean flow velocity and the discharge-weighted sediment concentration. Accurate determination of suspended solid requires a discharge-weighted sample of suspended sediment along each sampling vertical (Morris and Fan, 1998).

Based on the differential equation for sediment diffusion in the 2D steady turbulent flow, Huang et al. (2008) have proposed the following formula for vertical distribution of suspended load concentration

$$C(y) = C_a\,[(a+k_s)/(y+k_s)]^Z$$

where $Z = \omega/(\beta_* \kappa U_*)$, $\beta_* = (\omega + 2V_e)/U_*$ and $V_e = \sigma_v/\sqrt{2\pi}\,\exp[-0.5(\omega/\sigma_v)^2]$

The variables in the formulae are as follows: $C(y)$ = Concentration at an elevation y from bed, C_a = Sediment concentration at the lowest measured point a (reference concentration), Z = suspension index, k_s = roughness height, ω = Settling velocity of sediment in quiescent layer, σ_v = Standard deviation of vertical velocity (a function of elevation y above the bottom), U_* = Shear velocity, κ = von Karman constant, and V_e = Effective laden-sediment velocity. According to Huang et al., 2008, this formula is simple and convenient for practical use, and avoids the existing deficiencies (infinite value of concentration at the bottom and zero value at the surface) in Rouse formula.

Huang et al., 2008 have also derived a theoretical elementary function from this new formula to calculate unit-width transport rate of the suspended load (q_s), which, they claim, avoids the contradiction between the lower integral limit and that of velocity distribution in the Einstein approach. This equation does not need numerical integration required in Einstein method. The equation is as follows:

$$q_s = 1.25\, U_* C_0 k_s \ln^2(1+1/\eta_0) \text{ for } Z=1$$

$$= 2.5\, U_* C_0 k_s (1-Z)^2 [(1-Z)(1+1/\eta_0)^{1-Z} \ln(1+1/\eta_0) + 1-(1+1/\eta_0)^{1-Z}] \text{ for } Z \neq 1$$

where η_0 (relative roughness)= k_s/h, C_0=sediment concentration at bed surface, h=depth of flow.

1.6.5. Deposition of sediment in rivers

Sediment deposition in rivers results in the formation of braid bars. The capacity of a reach for transport of sediment increases if the banks are unerodible and the channel width is confined there. Consequently, the likelihood of sediment deposition in that location reduces. Since bank erosion cannot take place there, already formed bars will also be removed as the flow increases. Thus, for the bars to become stable and divert the flow, the banks must be sufficiently erodible, so that they rather than the incipient bar give way as the flow is diverted around the depositing bar. Sediment transport and a low threshold of bank erosion provide the essential conditions of braiding. Rapidly fluctuating changes in stage and heterogeneity of the bed material may contribute to braiding by creating instability of the transport regime. Braiding is a type of adjustment in a channel possessing particular bank material in response to a debris load too large to be carried by a single channel (Leopold et al., 1964).

1.6.6. Meandering-Braiding transition

Channel pattern depends on discharge, slope and, bank and bed materials. Leopold and Wolman (1957) related transitional slope (S^*) and bankfull discharge (Q in m^3/s) for meandering-braiding transition as:

$$S^{*}=0.013\ Q^{-0.44}$$

Millar (1998) transformed the Parker (1976) criteria for transitional slope (S^{*}) to the following relation

$$S^{*}=0.0002\ (D_{50})^{0.61}\varphi'^{1.75}Q^{-0.25}$$

where D_{50} = median sediment diameter for the banks and bed surface (m), φ′ = bank sediment friction angle and Q = bankfull discharge (m^3/s). Values of S^{*} were calculated using field data of 176 meandering rivers and 32 braided rivers and were plotted against observed values of slope. The points representing meandering rivers fell in the region where $S<S^{*}$ and those for the braiding rivers (except three) fell in $S>S^{*}$ region. This relation is applicable to Lane’s Type-I braided rivers, where braiding is a result of the steep gradient (Lane, 1957). Type-II Rivers that braid due to channel aggradation, such as those in alluvial fan environment, can also occur at moderate to low gradients. The three braided rivers that plotted in the meandering region may be Type-II braided rivers. Thus this relation helps to discriminate between braided rivers resulting from steep gradient and channel aggradation. The friction angle parameter, φ′, can be used as a quantitative index of bank vegetation on the erodibility or stability of the bank sediment (Millar and Quick, 1993). Local values of φ′ that are species-specific can be derived and used in the design of bioengineering bank stabilization projects. Training of braided rivers into meandering form may be done with the help of this relation.

By varying φ′ in their analytical hydraulic geometry model, Millar and Quick (1993) were able to demonstrate the influence of bank vegetation on the channel geometry. As the value of φ′ was reduced, the resultant channels became wider, shallower and steeper, suggesting a tendency towards a more braided morphology. Values of about 40° are typical of banks with little or no vegetation, while values up to

75° or greater have been determined for banks that are densely vegetated by deep-rooting species.

1.6.7. Evolution and modification of sediments

Compositional and textural characteristics of the initial detritus are modified by abrasion and sorting during transport, when the sediments are carried away from their source area. While sediment is in transit, chemical alteration takes place during temporary storage in alluvial systems (Johnsson and Meade, 1990). In principle, the total amount of time available in relation to the total amount of energy defines the relative contribution of mechanical and chemical alteration of particles (Figure 1.4) (Weltje and Eynatten, 2004).

Within fluvial systems, current flow is nearly unidirectional and progressive reworking of fine sediment commonly leads to the finest material being transported furthest downstream. Hence fluvial systems are typically characterized by downstream reductions in mean grain size.

1.7. Sediment as a carrier of pollutants

Sediment is an important component of a river and plays a major role in hydrological, geomorphological and ecological functioning of river basins. Sediment provides substrates for organisms and creates fertile soils in floodplains highly suitable for agricultural production. On the other hand, the removal of sediments from harbours, navigation channels, locks, floodplains, and river stretches incur heavy capital costs. Anthropogenic emissions of excessive pollutants have caused a rapid deterioration of sediment quality. Construction of hydraulic structures, deforestation, urbanization, etc. has altered the hydrodynamic conditions of many rivers of the world (Forstner and Owens, 2007).

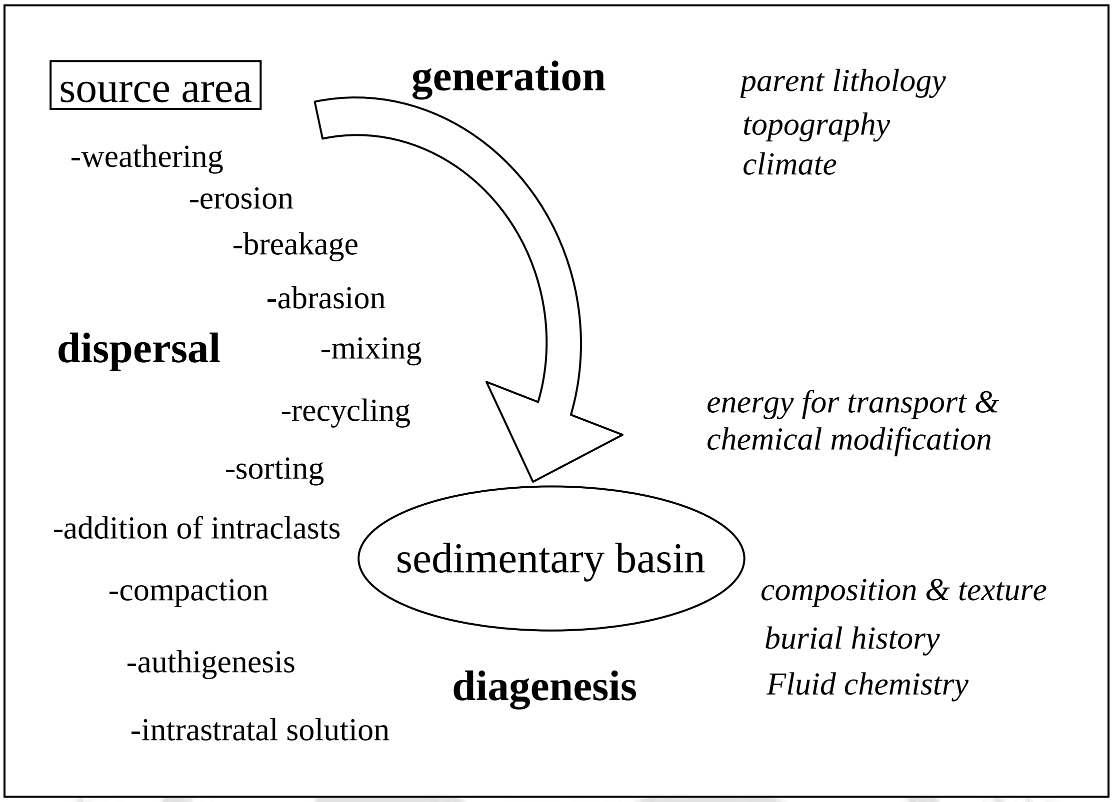


Figure 1.4: Main steps in sediment evolution (bold) and principal processes that modify the composition of clastic sediments along the pathway from source area to sedimentary basin. Controlling factors (italic) are shown on the right (Weltje and Eynatten, 2004).

Sediment acts both as a source and a sink of pollutants by desorption from and sorption to it (Forstner, 1987; Gonzalez et al., 2000). Some forms of aquatic life (e.g., predators) are affected by turbidity of water. Some pathogens may attach to sediment particles, such as clays, and this could "shield" them from disinfectants used in water treatment processes. Deposited contaminated sediment was termed as "chemical time bomb" by Stigliani (1991), because these may be released to the overlying water under appropriate conditions (turbulence, change in pH, etc.).

1.7.1. Classification of pollutants

Toxic substances can be classified by their functions (e.g., pesticides, cleaning products, fuels, etc.) or their primary industrial association (agriculture, petroleum refining, textiles, etc.). Classification may be based on chemical criteria also. EPA's "priority pollutants" is the most commonly used classification. It consists of 129 inorganic and organic toxicants. The inorganics consist of heavy metals and other contaminants such as asbestos and cyanide. The organics are divided into nine classes. Thus, the classification is a mixed bag of usage (pesticides) and some broad chemical classes

1.7.1.1. Various forms of pollutants

Pollutants exist in various interactive forms (Figure 1.5) depending upon the prevailing physico-chemical conditions (e.g., pH, Eh, salinity, CEC, DO, TOC) in the aquatic environment. Metals may exist in dissolved forms as free metal ions or complex molecules, or in particulate forms adsorbed to the surface of solid particles or as precipitates (mostly as sulfides). In free mode (the most toxic), metals are transported with the water and easily taken up by organisms. The particulate associated forms are relatively inactive. In sediments under natural conditions (anoxic, reduces, near neutral pH) only a small fraction of heavy metals is dissolved; the major portion is bound by sulfides or by structurally complex, large organic compounds. Under aerobic conditions, removal of metals from dissolved phase occurs by absorption and coprecipitation of metal ions or hydroxides with iron and manganese hydroxides which form coatings on the surface of particles. The release of metal ions by sulfides upon oxidation may be counteracted by these processes. Organic micropollutants may also exist in either dissolved or particulate bound forms. Generally the latter are less bioavailable. For most compounds the unionized dissolved forms are the most toxic. A decrease in pH accelerates dissociation process and increases toxicity. However, most chemical changes do not affect the mobilization of organics (Bray, 2008).

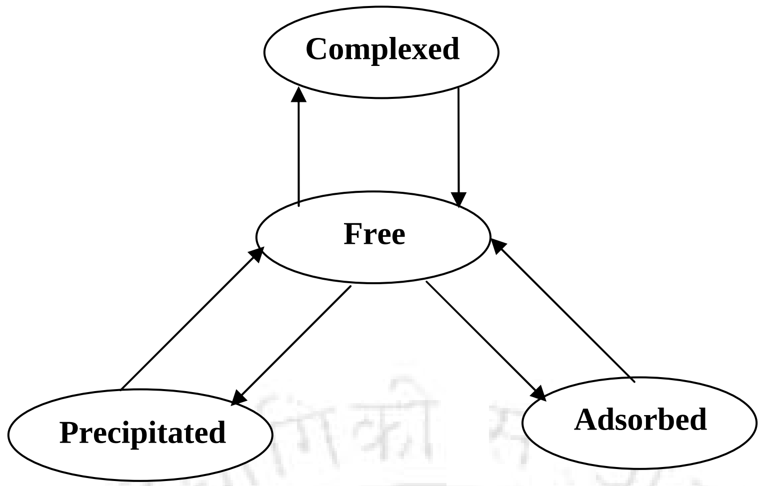


Figure 1.5: Basic forms of heavy metals in the aquatic environment and transformation routes (Source: Goossens and Zwolsman, 1996)

1.7.1.2. Solid-Liquid partitioning of pollutants

Transport, fate and ecosystem impact of toxicants is intimately connected with how they partition or associate with solid matter in and below the water body. Unlike conventional pollutants (biodegradable organic matters, nutrients), toxic substance analysis must distinguish dissolved and particulate forms as certain mechanisms differentially impact the two forms. For example, volatilization (loss of contaminant from the water to the atmosphere) acts only on the dissolved fraction and settling acts solely on the particulate-associated fraction.

Following equations describe solid-liquid partitioning of total concentration of pollutants:

$$C = C_d + C_p;\ C_d = F_d\, C;\ C_p = F_p\, C$$

$$F_d = 1/(1+K_d.m);\ F_p = (K_d.m)/(1+K_d.m)$$

where C = total contaminant concentration (μg m^{-3}), C_d and C_p = dissolved and particulate components (μg m^{-3}), F_d and F_p = dissolved and particulate fractions of the total contaminant ($F_d + F_p = 1$), K_d = a partition coefficient ($m^3\ g^{-1}$) and m = suspended solids concentration ($g\ m^{-3}$).

For weakly sorbing contaminants (low K_d) in systems with low suspended solids (low m), the contaminant will be predominantly in the dissolved form. For strong sorbers in turbid systems, the contaminant will be strongly associated with suspended solids (Chapra, 1997).

Clay minerals [e.g., Kaolinite, $Al_2Si_2O_5(OH)$] in the sediments possess large surface areas and can adsorb cations on their surfaces. Often the metal ions displace H^+ ions from the OH groups on the surface of the clay particles (Brown et al., 1991):

$$M^+ (aq) + H\text{-}O\text{-}Clay \rightleftharpoons H^+ + M\text{-}O\text{-}Clay$$

This situation gives rise to pH-dependent equilibria. Higher the concentration of $H^+(aq)$, the more the equilibrium is shifted to the left. Water of the Brahmaputra River is often basic and more metals should get transported through sediments by adsorption. Mandal (2005) found the average pH of the Brahmaputra River near the sampling sites of present study to exceed 8.0 most of the times in a study extending one year. According to Viers et al. (2009), most of the elements (except Ca, Mg, K and Na) in a river are mainly transported by the solid phase.

The surface charge of a particle is a function of a number of different processes as represented by the following equation (Eby, 2004):

$$NC = FC + NP + ISC + OSC$$

where NC is the net charge, FC is the fixed charge due to substitutions in the crystal structure, NP is the net proton charge due to binding or release of hydrogen ions from the surface, ISC is the charge due to the presence of inner-sphere complexes (complex formed by direct attachment of cations to oxygen ions exposed at the particle surface), and OSC is the charge due to the presence of outer-sphere complexes (complex formed by attachment of water molecules of solvated cations with exposed surface functional groups). If the net charge is not zero, it is balanced by the ions in the diffuse double layer adjacent to the surface. As NP, ISC and OSC vary as a function of pH, surface will have no charge (point of zero charge) at some pH. A point of zero net proton charge (*PZNPC*) may be defined, which occurs when the charge due to binding and release of protons (NP) is zero. At pH values below *PZNPC*, particles will have positively charged surface; at pH values above *PZNPC*, particles will have negatively charged surface. Thus, adsorptive characteristics of particles depend on the relationship between pH and surface charge.

Table 1.6: Point of Zero Net Proton Charge (Kehew, 2001)

Material	pH_{pznpc}	Material	pH_{pznpc}
α-$Al(OH)_3$	5.0	δ-MnO_2	2.8
γ-AlOOH	8.2	SiO_2	2.0
Fe_3O_4	6.5	Feldspars	2.0-2.4
α-FeOOH	7.8	Kaolinite	4.6
α-Fe_2O_3	8.5	Montmorillonite	2.5
$Fe(OH)_{3\,(am)}$	8.5	Albite	2.0

Metals are readily adsorbed by the surface over a relatively narrow pH range after the surface becomes negatively charged (Figure 1.6). The degree of adsorption increases with increasing pH. Ions with higher selectivity are adsorbed at lower pH. Selectivity series (order in which the ions are preferentially adsorbed, from most strongly adsorbed to least strongly adsorbed) for a subset of transition metals are as follows: $Cu^{2+} > Ni^{2+} > Co^{2+} > Fe^{2+} > Mn^{2+}$.

Surface of particle in aqueous solution acquires charge due to ionization of chemical groups on it. Biological surfaces usually have proteins as part of the surface structure, which have carboxylic (COOH) and amine (NH_2) groups. These are weakly

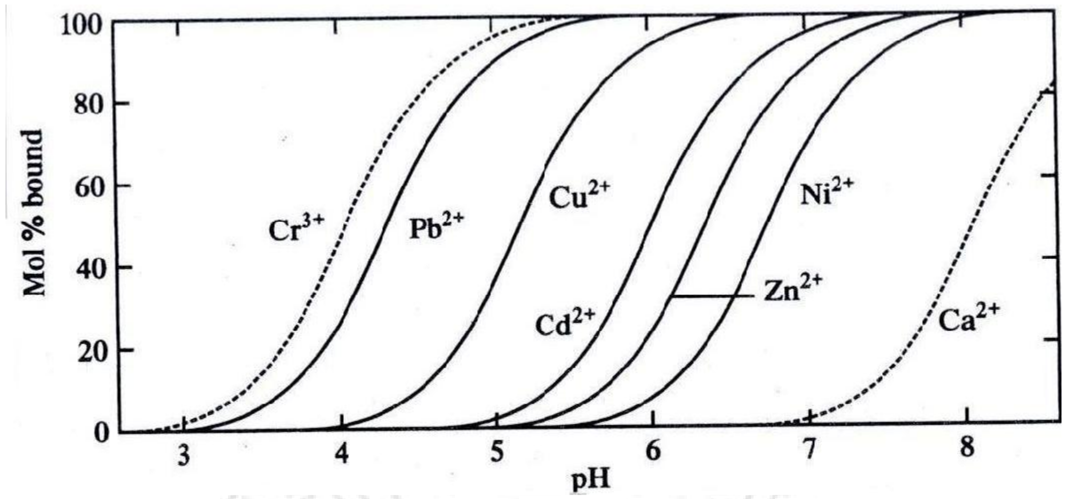
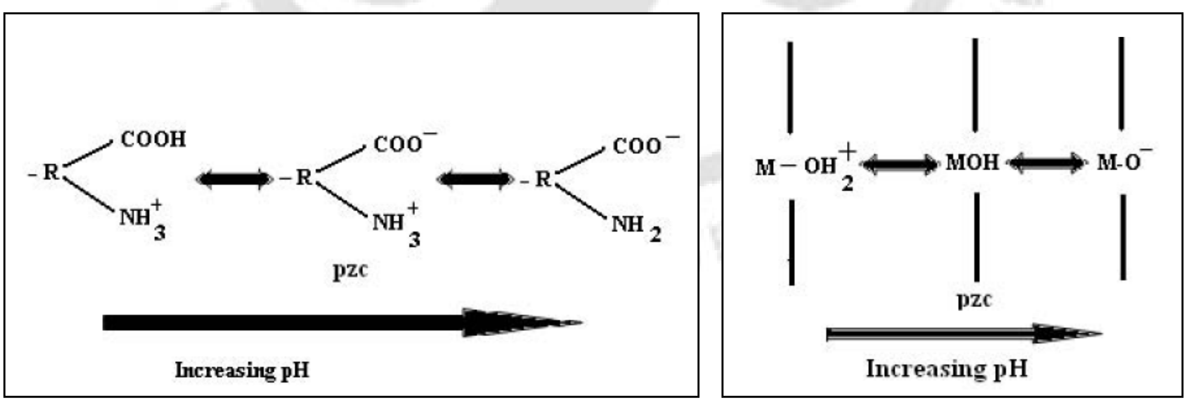


Figure 1.6: Adsorption of metal cations as a function of pH (Source: Cited by Eby, 2004 from Stumm and Morgan, 1996)

acidic and basic groups, respectively, which ionize in the manner shown in (Figure 1.7 A). At low pH, carboxylic groups are not dissociated and hence uncharged, whereas the amine groups are protonated and have a positive charge. At high pH the carboxylic groups dissociate to give a negative charge and the amine groups lose their proton and are uncharged. So such surfaces are positively charged at low pH and negatively charged at high pH. There is a characteristic pH value called point of zero charge (PZC) at which the number of negatively charged surface groups just balances the number of positive groups.



(A) (B)

Figure 1.7: Ionization of (A) surface carboxylic and amine groups, (B) metal hydroxide (MOH) groups at an oxide surface (Gregory, 2006)

For many biological surfaces (e.g., of bacteria and algae), the PZC is in the region of pH 4-5, so that in most natural waters such particles are negatively charged. Many inorganic particles (e.g., sediments) in the aquatic environment are negatively charged by virtue of an adsorbed layer of natural organic matter. Metal oxide (Al_2O_3, Fe_2O_3, TiO_2, etc.) surfaces form amphoteric hydroxides (e.g., AlOH), which can ionize to give either positive or negative charge (Figure 1.7 B). Again, the surface is positively charged at low pH and negatively charged at high pH. For oxides, PZC values (SiO_2 – 2; TiO_2 – 6; Fe_2O_3 – 8; Al_2O_3 – 9; MgO – 12) depend on the acid-base properties of the metal and vary over a wide range (Gregory, 2006).

1.7.1.3. Particulate fraction-the major carriers of pollutants

The largest proportion of the contaminant load in sediment systems is transported by the particulate matter. For example, Gibbs (1977) suggested that up to 90% of the metal load is transported by sediments in rivers, but this can vary from metal to metal. Similar observations have been made for organic contaminants, such as chlorinated organic compounds. Some metals, under low pH condition, can be transported in solution. The partitioning of contaminants between the dissolved and particulate load in aquatic systems depends on both physical and chemical factors, including pH, redox potential, sediment mineralogy, sediment texture, suspended sediment concentration and sediment grain size. Metals in particular have been shown to be enriched in the fine silt and clay fractions of sediments, as a result of their large surface area, organic and clay contents, surface charge and cation exchange capacity.

Gaillardet et al. (2003) reported the proportion of a given element in dissolved phase relative to the bulk solution by the following relation:

$$D = 1/(1+K_D*TSS)$$

where D = proportion of the element in dissolved form, K_D = concentration in the suspended sediment by the dissolved concentration, and TSS = total suspended sediment concentration. Assuming an average value of 350 mg/L for TSS of World Rivers (Berner and Berner 1987), Gaillardet et al. (2003) showed that, even for the most mobile elements, the dominant form of transport is in solid form. Knowledge of chemical composition and material fluxes of suspended solids, therefore, is necessary for estimating elemental fluxes from the continent to the oceans. Important carriers for trace element in suspended particulate matters are clay minerals, along with Fe, Al and Mn oxides/hydroxides as well as particulate organic matter (Hochella and White, 1990).

1.7.1.4. Concentration of metals within sediment flocs

Flocs possess anaerobic zones within the core of the floc where Extracellular Polymeric Substance (EPS) densities are usually the highest and oxygen may be depleted (Simon et al., 2002). Such gradation in redox potential may result in the fixation or mobilization of metals within the flocs. Generally, an anaerobic zone will promote metal uptake. pH gradients set up within a floc will also affect the migration of metal ions within the floc matrix through diffusional processes (Warren and Haack, 2001).

Bulk metal analysis provides little insight into the factors that control the transport and interaction of contaminants with/within the sediment particles. Traditional geochemical relationship has demonstrated that as particle size decreases, the potential for contaminant uptake increases (Droppo and Leppard, 2004). This relationship is, however, based on individual particles and does not reflect the true structure by which sediment and contaminants are transported (i.e. as flocs). While metal binding to individual clay particles prior to flocculation occurs, metals may be transformed, relocated within the floc matrix, or added to by the diffusion and electrochemical processes operating within the floc. These processes, in conjunction with microbial metabolism, chemical precipitation and co-precipitation, dissolution and volatilization, are those that dictate the dynamic metal concentrations within the floc (Warren and Haack 2001).

While it is not feasible to fully understand the complex relationship of floc-metal interchanges, sequential extraction (Tessier and Campbell 1988), even with its limitations, does provide insight into the relative partitioning of metals within the flocs (although still with a bulk sample).

A preliminary survey of Hamilton Harbour (Droppo and Leppard, 2004) surficial fine grained laminae (SFGL) suggests that both Cd and Pb were primarily bound within Fe-Mn oxides (60-80%). Similar findings have been found for urban sediments and urban impacted rivers by Stone and Marsalek (1996), Droppo et al. (1998) and Sutherland and Tack (2000). Fe-Mn oxides are often manifested as precipitated crystalline forms or coatings and often dominate the geochemical reactivity of the sediment component. These forms of oxides are often smaller and more diffusive than chemical precipitates and as such possess extensive surface areas for metal uptake (Warren and Haack 2001).

Copper analysis revealed a common association with the organic fraction of the sediment (55-90%) (Droppo and Leppard, 2004). This organic fraction is heterogeneous and can include viable or non-viable bacteria, humic and fulvic acids and the colloidal fraction contributed by the extensive EPS network of the flocs and bacteria. Organics are effective scavengers of metals due to their large surface areas and multiple surface functional groups. Small organic molecules are generally more labile and taken individually may have a lower residence time in aquatic systems (Warren and Haack, 2001). However, organic molecules often are adsorbed onto mineral surfaces and when incorporated in flocs, these organic materials contribute to floc building and influence the behaviour of metals (Organic coating can inhibit or enhance metal binding-Warren and Haack 2001). Bacteria themselves possess surface functional group and can sorb metal species to their surface although this process could be complicated by the bacterium or other substances dissolved in the water (Warren and Haack, 2001; Chatellier et. al., 2004).

1.8. Some sediment related problems

1.8.1. Sedimentation in reservoirs

Reservoir construction is one of the greatest changes that have affected continental aquatic systems in the past 100 years (Meybeck, 2003b). They store more than 30% of river sediments at global scale (Vorosmarty et al., 2003), which exceeds 90% for some basins like Colorado, Rio Grande, Nile and Volga (Meybeck, 2003b). Reservoirs assume the vital functions of providing water supply for domestic, agricultural and industrial uses, generating hydroelectric power and reducing flood intensity by acting as detention basins. Sedimentation reduces their efficiencies to provide these intended benefits resulting in serious economic loss. The World Bank estimates that on a global basis the average replacement cost of the annual reservoir storage capacity loss due to siltation alone is approximately 6 billion dollars (Fan, 1998).

Maintenance dredging is often required to remove deposited sediments, which may lead to sediment resuspension increasing turbidity level and pollutant (sorbed to sediment) remobilization. Relocation of dredged sediment may be another problem. Soil conservation in the watershed upstream is often a cost-effective way of preserving the storage capacity of the reservoir(s) downstream (Fan, 1998). Sediment management has become primary importance for the safety, reliability and longer life of infrastructure projects like hydropower, irrigation and drinking water projects.

1.8.2. Erosion of turbine components

Fractions of suspended load settles down in settling basins or reservoirs and the rest passes through turbines causing wear of different components (buckets, nozzle, etc.). This problem exists for all kinds of turbines. Erosion rate increases with the sediment load. The coarse size particles cause more erosion compared to fine size particles. For same particle size, erosion rate increases with the increase in quartz content. Also, for a given quartz content, the erosion rate increases with the particle size. Bajracharya et al., (2008) derived a relationship between erosion rate and particle size at different quartz content levels based on samples from CHEP plant and Chimile River of Nepal as follows:

$$\textbf{Erosion rate } \alpha \textbf{ a (size)}^{b}$$

They reported that values of (a, b) increased with the amount of quartz in the sediment, which were (351.35, 1.4976), (1199.8, 1.8025) and (1482.1, 1.8125) for 38%, 60% and 80% quartz respectively.

1.8.3. Channel aggradation and degradation

The natural supply and flow of sediment along a river system are interrupted by construction of dams and impoundments. Channel aggradation occurs upstream of these constructions and increases the flood frequencies in those areas. Dramatic reduction in sediment supply downstream of the impoundment leads to “hungry waters” whereby the river compensates for the reduced load by downcutting and lateral erosion (Kondolf, 1997).

1.8.4. Occurrence of floods

Floods occur when the discharge of the stream becomes too high to be accommodated in the normal stream channel. When the discharge becomes too high, the stream widens its channel by overtopping its banks and flooding the low-lying areas surrounding the stream. The carrying capacity of a river or a stream drastically reduces due to channel aggradation by sediment deposition. Landslides sometimes block the paths of various tributaries coming down from mountains like the Himalayan ranges, inundating large floodplain areas in Assam and Bangladesh plains. Floods cause heavy damage to lives and property. In 1991, more than 200,000 deaths resulted from flooding and associated tropical cyclones in Bangladesh. In 1963, massive landslides into the reservoir behind the Vaiont Dam in Italy caused water to overtop the dam killing 3000 people (http://www.tulane.edu/~sanelson/geol204/riversystems.htm).

1.8.5. Increased cost of water treatment

Drinking water treatment cost increases with sediment concentration by larger volume of sludge generation and erosion of pumping facilities. Sediment also provides "shielding" action to pathogenic organisms necessitating the use of more disinfectants.

1.9. Sediment management issues

Most large river basins throughout the world are highly populated and / or modified by human activities (Forstner and Owens, 2007). There are many users and uses of sediments within a basin (Figure 1.8) and site specific interventions may adversely impact other users and uses of sediments (Owens 2005). Sediment management strategies (e.g., appropriate land use / management) should be adopted in a river basin scale as source control, in many cases, are considered to be optimal long-term solution-environmentally, socially and economically (Forstner and Owens, 2007).

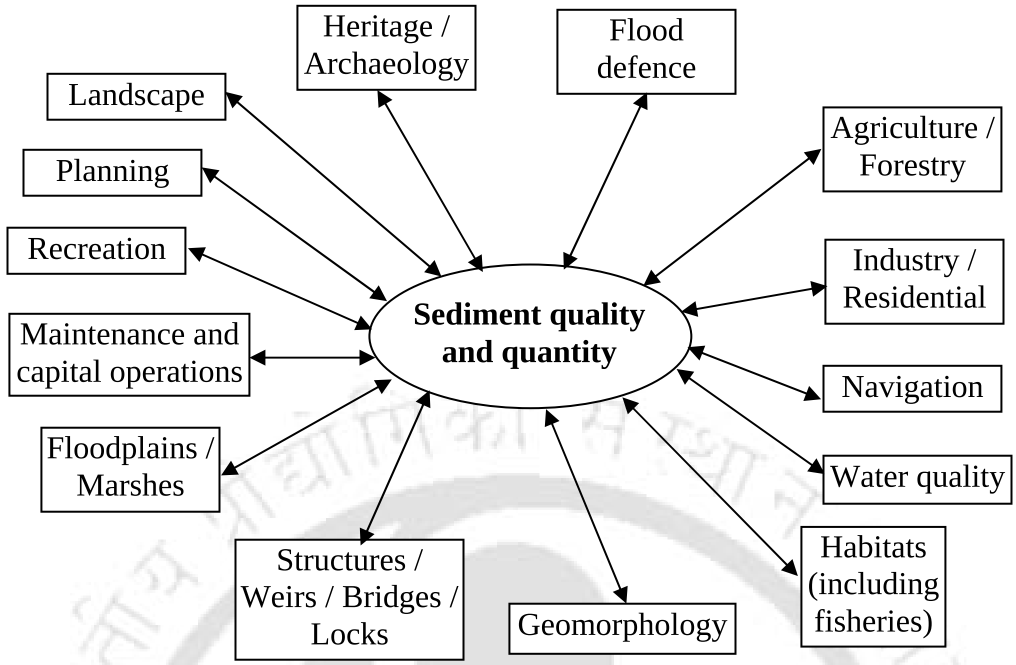


Figure 1.8: Schematic representation of some of the main influences and impacts on sediment within a river basin (Owens et al., 2004)

1.10. The Brahmaputra River, its discharge and sediment load

1.10.1. The Brahmaputra Basin

The Brahmaputra basin covers an area of 580,000 km^2 extending from 82° to 97°50' E longitudes and 25°10' to 31°30' N latitude (Bora, 2004). It is bounded on the north by the Kailash and Nyen-Chen-Tanghla ranges of mountains (Figure 1.11); on the east by the Salween River basin and the Patkai range running along the Indo-Myanmar border; on the south by the Nepal Himalayas, the Naga and Barail ranges and the Meghalaya Plateau; and on the west by Ganga river basin. The maximum meridional extent of the basin is 1540 km along 29°30' N latitude and maximum latitudinal extent is 780 km along 90° E longitude (Sarma, 2004). The valley is long and narrow, being only about 80 km wide on an average (Purkait, 2004).

Compared with the vastness of the drainage area, the average width of the

Brahmaputra (6-10 km) is too narrow to carry the full load of the surface water within the banks of the river. The banks are over flown causing floods (Barman, 1981).

1.10.1.1. Geology of the Brahmaputra Basin

The greater part of the Brahmaputra valley is made up of new alluvium of recent deposition overlying Tertiary, Mesozoic and Archaean bedrocks. Along the piedmont zone there occur some patches of older alluvium extending along the interfluves of the tributaries flowing from the Himalayan foothills. The soils of the Meghalaya plateau and the Mikir Hills in the south are of laterite and loamy silt and fine silt types (Bora, 2004). Soils derived from the tertiary sandstones of the lower Himalayas are friable in nature (Purkait, 2004). They consist mainly of sands with admixtures of cobbles and boulders having lower threshold of erosion (Purkait, 2004).

The Himalayan watershed of Brahmaputra is divided into four topographic units which rise progressively to the north (Goswami, 1985):

- The sub-Himalayas, with average elevation (above mean sea level) of 1000 m, consist of many raised, relatively young terraces containing mostly tertiary sandstones (Gansser, 1964).
- The middle Himalayas, with an average elevation of 4000 m, contains lower Gondwana (Palaezoic) deposits of shales, slates and phyllites with a thick horizon of basaltic rock on its top.
- The greater Himalayas, with an average elevation of 6000 m, are made up of granites and gneisses.
- The trans-Himalayas of Tibet, with an average elevation of 4500 m, consists of sedimentary formations of Palaezoic to Eocene age (Wadia, 1968).

The Patkai-Naga ranges (average elevation 1000 m) lie to the east and southeast of Brahmaputra valley which contain tertiary formations with large number of active faults. The Meghalaya plateau and the Mikir hills (elevation 600-1800 m) form a part of the stable Indian Peninsular block of Precambrian age. These are mainly made up of gneisses and schists. The Brahmaputra valley in Assam consists of clay, silt, sand and pebbles in a 200-300 m thick (approximately) layer of recent alluvium (Geological Survey of India, 1974).

Hu Ming-Hui et al. (1982) have reported that the dominant lithology of Tibetan Himalayas, where the Brahmaputra River originates, consists of reduced shales, gneisses, carbonates, and some volcanic rocks at a few places (Cited by Mahanta and Subramanian, 2004).

According to Sarin et al. (1989), the lithology of the southern slopes of the Tibetan Himalayas along the course of the Brahmaputra is dominated by reduced shales, gneisses and volcanic rocks. The river drainage basin in the Assam Valley is characterized by recent and Pleistocene alluvium, and the river encounters granite and gneiss projections of the Mikir Hills in the central part of the valley (Sarin et al., 1989).

1.10.1.2. Climate in the Brahmaputra Basin

Climatically the Brahmaputra basin can be divided into two zones (Figure 1.11): area to the north of the Himalayan mountain ranges classified as “Mountain climate” and the southern part of the basin classified as “Tropical monsoon climate” (Jain et al., 2007). Climate in the mountain zone is cold, dry and arid. Tropical monsoon climate is warm and humid, and experiences high rainfall, especially during June to September (Jain et al., 2007).

The basin experiences wide seasonal variations of temperature. The monthly means of daily maximum and minimum temperatures of four stations are presented in Table 1.7.

Table 1.7: Monthly mean of daily maximum and minimum temperature (in °C) of four stations located in the Brahmaputra basin (Jain et al., 2007)

Month	Lhasa		Dibrugarh		Tezpur		Guwahati	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
January	14	-12	25	7	25	9	26	7
February	16	-12	27	9	28	10	29	8
March	18	-8	31	12	33	13	34	11
April	22	-4	32	15	34	17	36	17
May	25	1	35	18	35	19	35	19
June	28	4	35	21	35	22	35	22
July	27	6	35	22	35	23	35	24
August	26	4	35	23	35	24	35	24
September	24	4	34	21	35	23	34	23
October	22	-5	33	17	33	18	33	18
November	17	-9	29	12	30	13	30	13
December	14	-13	26	8	26	9	27	8

The basin as a whole has the average annual rainfall of 230 cm with a variability of 15-20%. The Himalayan sector receives 500 cm rainfall per year, the lower ranges receiving more than the higher areas (Goswami, 1985). Within the valley reach in Assam,

Table 1.8: Mean monthly rainfall and rainy days observed at four stations located in the Brahmaputra basin (Jain et al., 2007)

Month	Lhasa		Dibrugarh		Tezpur		Guwahati	
	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days	Rainfall (mm)	Rainy days
January	3	1	38	7	15	3	10	2
February	13	1	62	10	27	6	4	5
March	8	1	103	14	48	8	25	6
April	5	1	241	18	153	12	145	10
May	25	3	307	19	271	19	236	15
June	53	8	500	22	308	18	312	18
July	122	13	536	24	348	19	312	20
August	89	10	451	22	331	18	261	16
September	66	7	352	21	210	16	167	15
October	13	2	152	8	104	6	71	5
November	3	1	53	4	23	3	14	2
December	0	0	16	3	6	2	4	1
Annual	400	48	2811	172	1844	130	1561	115

NB: A day having rainfall more than 0.3 mm is termed as a rainy day rainfall is more towards the northeast and gradually decreases towards the west (Jain et al., 2007). Mean monthly rainfall and rainy days at four stations located in the Brahmaputra basin are shown in Table 1.8. Rainfall periods may be divided into winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November). Almost 65% of the rainy days occur in the monsoon season and 20% in the pre-monsoon season. The post-monsoon periods experiences very low rainfall, of the order of 3% to 6% of the annual value (Jain et al., 2007).

1.10.2. The Brahmaputra River

The geological history of the Brahmaputra valley indicates that the Brahmaputra is a very young river and its present configuration took shape only during the Pleistocene and recent times; and in spite of its low gradient in the plains area its erosive power is still very active and has got many changing courses in recent times (Barman, 1981). In upper Assam, the Brahmaputra River has produced the largest river island at Majuli, which measures 90 km in length and 20 km in breadth (Barman, 1981).

The Brahmaputra is an antecedent snow fed river, which flows across the rising young Himalayan Range. It flows through three countries, viz., China, India and Bangladesh. The course of the River is shown in Figures 1.9 and 1.11.

The slope of the river (Figure 1.10) is steep when it crosses the Himalayas. Large amount of sediment deposition due to sudden decrease of slope near Pasighat results in choking up of the channel and development of prominent braiding pattern. About 83% of the course of the river in Assam is braided (Sarma, 2005) (Figure 1.12 C & D). The river flows in single channel for three reaches (Silghat, Pandu, and Jogighopa) in Assam, where the channel is confined on both sides by resistant granitic (Goswami, 1985) hills

(Figure 1.12 A). Pandu is the narrowest reach (length = 12 km; Breadth = 1.11-1.69 km) where water depth varies from 18.2 m in low stage to 27.4 m in high stage (Sarma, 2005). Salient features of the Brahmaputra Basin / River (Goswami 1998) are furnished in Table 1.9.

Table 1.9: Salient features of the Brahmaputra Basin (Goswami 1998)

Catchment area (km^2)		
within China		293000
within India		195000
within Bhutan		45000
within Bangladesh		47000
Total		5800000
Length (km)		
within Tibet (China)		1625
within India		918
within Bangladesh up to the confluence with the Ganga		337
from source to confluence with the Ganga		2880
Gradient		
Reach within Tibet		0.00260
Reach between Indo-China border and Kobo in India		0.00190
Reach between Kobo and Dhubri		0.00014
First 60 km within Bangladesh		0.00009
Next 106 km reach within Bangladesh		0.00008
Next 92 km reach within Bangladesh		0.00004
Next 79 km reach within Bangladesh		0.00003
Discharge observed at Pandu, Assam (m^3s^{-1})		
Maximum (on 23-08-62)		72794
Minimum (on 20-02-68)		1757
Mean annual flood discharge		51156
Mean annual dry season discharge		4420
Mean monsoon flow (June to October) (Mm^3)		
Shigatse, Tibet		507
Pasighat, India		3979
Discharge per unit area of basin ($m^3s^{-1}km^{-2}$) and Sediment yield (metric tons km^{-2})		
Location	Discharge	Sediment yield
T'sela D's Zong (China)	0.01	100
Pasighat (Arunachal)	0.023	340
Pandu (Assam)	0.03	804

Bahadurabad (Bangladesh)	0.032	1128
Sediment load during flood at Pandu (metric tons)		
Average annual suspended load		4×10^8
Daily mean sediment load		2.12×10^6
Basin Land Use (km^2)		
Total forest cover		114992.08
Total agricultural land		50473.84
Some other characteristics		
Mean Basin Rainfall (Excluding Bhutan and Tibet)		230 cm
Basin Population in India		30.4 million
Population density		143 persons km^{-2}

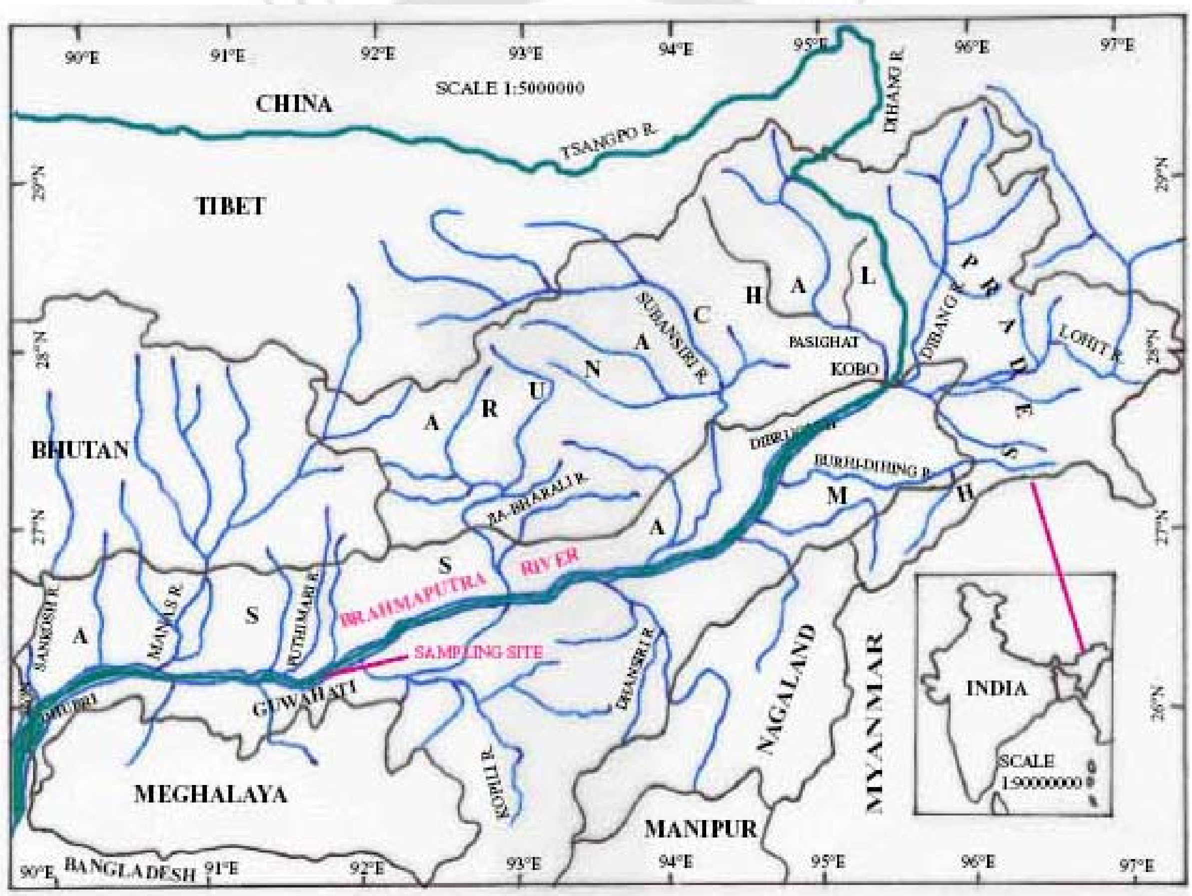


Fig. 1.9: The Brahmaputra River in Assam, India and the location of the sampling site (Source: Assam Book Depot's School Atlas, 3rd Edition, 2010)

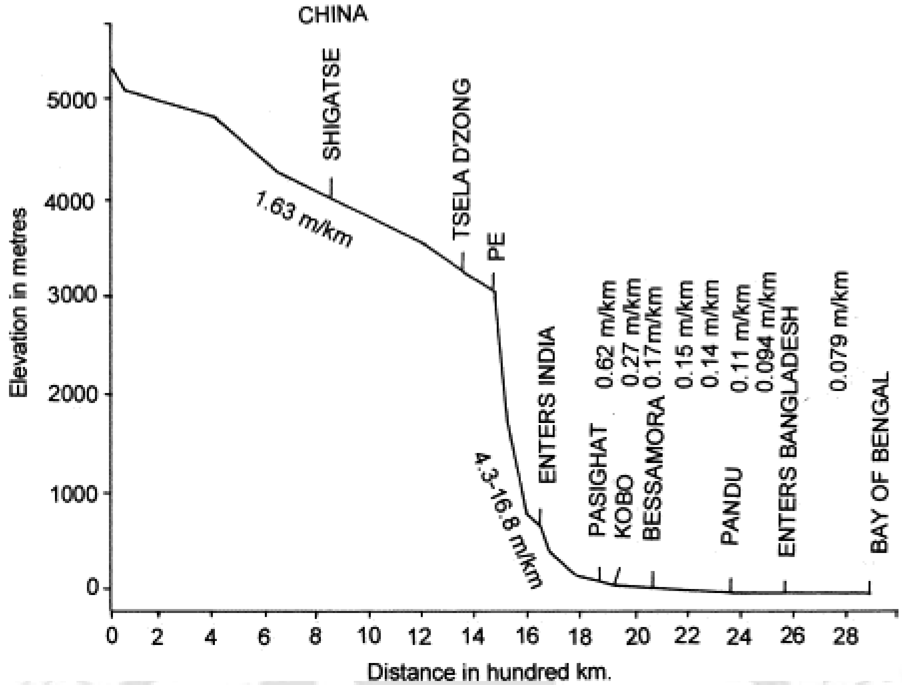


Fig. 1.10: The longitudinal profile of the Brahmaputra River (modified after WAPCOS, 1993) (Sarma, 2005)

1.10.2.1. Discharge of the Brahmaputra River

The average annual runoff of the Brahmaputra at Pasighat and Pandu in India as well as at Bahadurabad in Bangladesh is 186,290, 494,357 and 589,000 million cubic meters, respectively. The monsoonal flow of the Brahmaputra at Tesla Dzong in Tibet is 36.27% of the flow at Pasighat, Arunachal Pradesh (WAPCOS, 1993).

The average discharge of the river at its mouth is 19830 $m^3 s^{-1}$ (Goswami, 1982). It carries 82% of its annual flow at Pandu (Assam) only during the rainy season from May to October. The mean annual maximum and minimum flows in the river during 1955-97 are 48161 and 3072 $m^3 s^{-1}$, respectively. On average, therefore, the maximum flow is more than fifteen times the minimum. The flow in the river is less than or equal to the mean annual flow about 51% of the time (Bora, 2004).

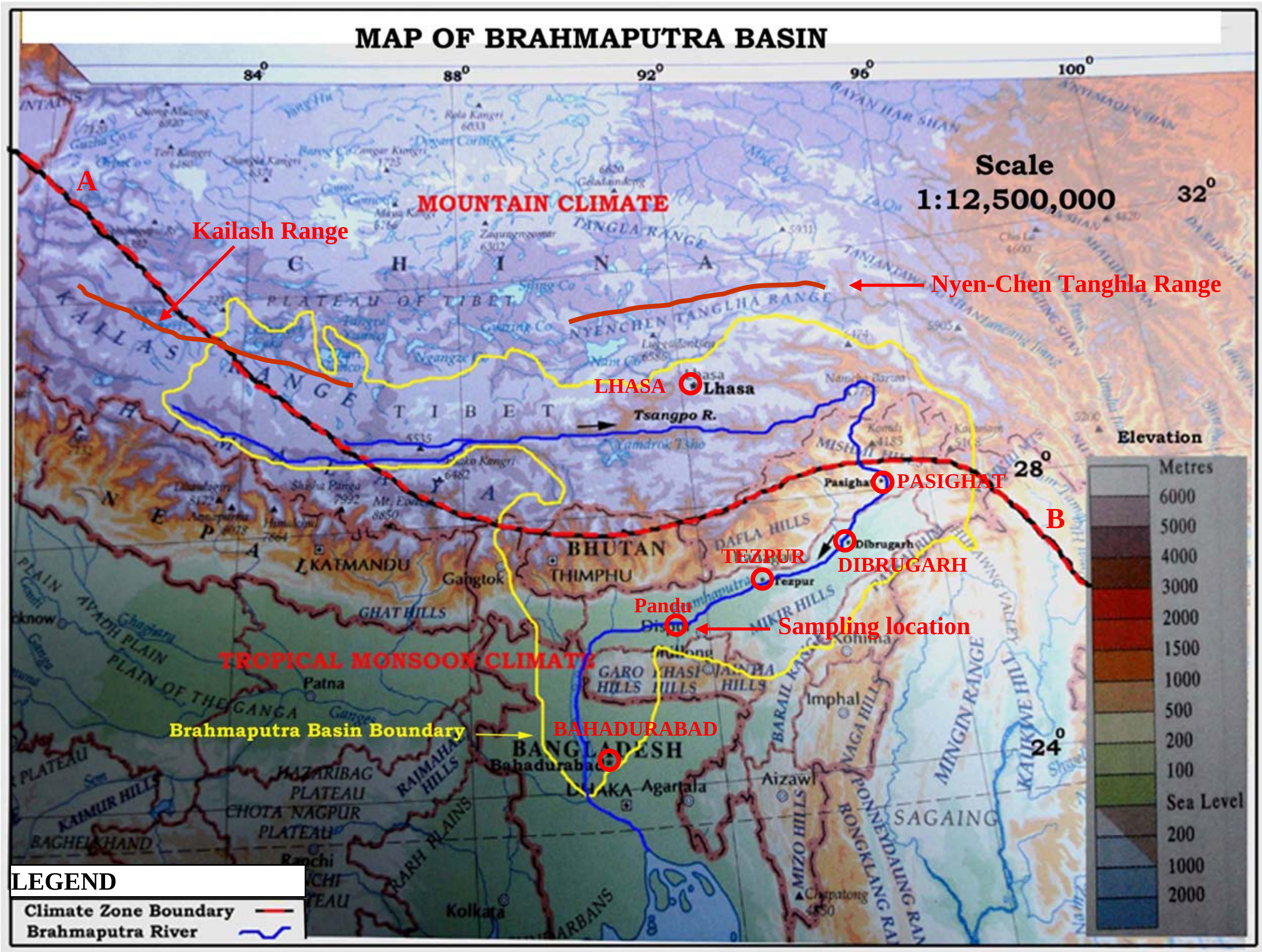


Figure 1.11: The Brahmaputra Basin (Sources: Map: Oxford School Atlas, 2009; Climatic zones' dividing line AB: Jain et al., 2007; Basin Boundary: www.wahidpolash.wordpress.com visited on 07-01-2012)

Figure 1.12: Nature of banks (A, B) and braid bars (C, D) of the Brahmaputra River (Photographs were taken by author)

1.10.2.2. Sediment load in the Brahmaputra River

The rank of sediment yield of the Brahmaputra is the second highest (1128 tons km^{-2} yr^{-1} at Bahadurabad, Bangladesh) in the world after the Yellow river (1403 tons km^{-2} yr^{-1}). At Pandu, Assam, the sediment yield of the river is 804 tons km^{-2} yr^{-1} (Goswami, 1998). The maximum and minimum sediment concentration values at Guwahati are 679 and 36 ppm respectively. The percentage breakdown of the surface sediment load is 12.5% coarse, 14.2% medium, and 73.3% fine (Datta and Singh, 2004). During the monsoon month from May to October the Brahmaputra caries an average daily sediment load of 2.12 million metric tons at Pandu, Assam (Bora, 2004). It carries a high volume of suspended load of the order of 402 million metric tons on average annual basis at

Pandu (Bora, 2004). The bed load of the Brahmaputra River is generally considered as 15% of the suspended sediment load (Datta and Singh, 2004).

The high intensity of monsoonal rains, easily erodible tertiary rocks of the Himalayan ranges, steep slopes, high incidence of landslides and high seismicity in the basin have rendered the river a highly water-carrying, sediment-yielding and heavily sediment laden one (Bora, 2004). Besides the natural causes, some human activities also contribute to the high rate of sediment load; most prominent among them is "Jhuming", the shifting cultivation. This is extensively practiced by the tribal communities living in the mountainous regions of the basin area, especially in Arunachal Pradesh and southern Assam hill ranges and is done by burning the forest and exposing the soil for cultivation. About 1.35 million hectares of the forest land remains under Jhum cultivation at any time. Heavy bank erosion by the Brahmaputra River takes place at different reaches owing to excessive sediment load, the erodible nature of the bank material (Figure 1.11 B), formation of *Char* Island, and consequent development channels (Datta and Singh, 2004). Bank material of the Brahmaputra are mostly composed of dominant proportions of fine sand and silt with occasional presence of clay being less than 5% (Bora, 2004; Sarma, 2005). The median diameter of bank and bed sediments of the river varies from 0.08 mm to 0.22 mm of which the finer size belongs to bed sediments (WAPCOS, 1993).

1.10.2.3. Tributaries and their sediment loads

The Indian section of the Brahmaputra River receives flows from a large number of (more than 100) tributaries flowing down the northern, northeastern and southern hill ranges. In the north the principal tributaries are the Subansiri, the Jia Bharali, the Dhansiri, the Puthimari, the Pagaldiya, the Manas, and the Champamati. Among these the Subansiri, the Jia Bharali, and the Manas are the trans-Himalayan Rivers. The principal south bank tributaries are the Burhi-Dihing, the Disang, the Dikhow, the Dhansiri (S), the Kopili and the Krishnai (Bora, 2004). The Brahmaputra River flows for about 670 km through the state of Assam along the Assam valley and within Assam, it receives flows from 103 tributaries-65 on the north and 38 on the south bank (Sarma, 2005).

Table 1.10: Average annual suspended sediment load of some important tributaries of the Brahmaputra River within its valley reach (middle reach) **(**Datta and Singh, 2004)

Sl No	Name of tributary	Name of observation site	Average annual suspended sediment load in ha.m.
1	Dihang	Ranaghat	7694
2	Dibang	Jiagaon	2620
3	Luhit	Digarughat	4650
4	Subansiri	Bhimpuraghat	2497
5	Jia-Bharali	N.T.Rd.Cr.	2143
6	Manas	Mathanguri	2038
7	Sankosh	Srirampur	594
8	Burhi-Dihing	Khowang	594
9	Disang	N.H.Cr.	70
10	Dhansiri (S)	Numaligarh	422
11	Kopili	Dharamtul	222
12	Puthimari	N.T.Rd.Cr.	371

The sediment yield of the north bank tributaries is approximately 5 to 6 times higher than that of the south bank tributaries (Datta and Singh, 2004). The tributaries that originate from the high Himalayan mountain ranges carry high sediment loads as these rivers flow through geologically younger Himalayan mountain ranges of unconsolidated sedimentary rocks with steep slopes and the area falls in one of the most earthquake prone belts of the world (Bora, 2004). As a result of these peculiarities, the north bank tributaries choke up their beds, leading to diversion of channels including river capture often accompanied by channel bifurcation, to modify the river system frequently (Bora, 2004). The tributaries originating from the southern (Assam) hill ranges carry less sediment load as these hill ranges are geologically much older and stable and of lesser height and have flatter bed slopes (Datta and Singh, 2004), and their drainage system exhibits a more or less conservative nature (Bora, 2004).

The Jia Bharali and the Manas in the north carrying average annual suspended sediment load of 2,013 ha.m. and 2,166 ha.m., respectively, are the leading tributaries in terms of sediment discharge. Of all the north and south bank tributaries, as many as fourteen have sediment yields in excess of 500 tons/km^2/year, the highest being 4,721 tons/km^2/year from the Jia Bharali basin. Besides the Jia Bharali, the other two trans-Himalayan tributary basins, viz., the Subansiri and the Manas yield 959 and 1,581 tons /km^2 /year respectively (Bora, 2004).

Over 70% of the annual average sediment load of the Brahmaputra River at Guwahati is contributed by the main river course Dihang and two tributaries Dibang and Lohit. These rivers carry very high sediment loads. The average percentage breakup of the suspended sediment at middle reach as coarse, medium and fine for the north bank tributaries are respectively 14.47, 29.25 and 56.28, and for the south bank tributaries are respectively 8.24, 17.00 and 74.76 (Datta and Singh, 2004).

Most of the tributaries of the Brahmaputra River form alluvial deltas at the foothill region where the river gradient abruptly changes from a steeper one in the mountainous region to a flatter one in the plains. Most of the suspended sediment carried by the rivers from mountainous region gets deposited in the river bed. Often these rivers are also found to change their course at this region when old channels get filled up with sediment. The north bank tributaries are more prone to such behaviour (Datta and Singh, 2004).

1.11. Research Need of studying sediments of the Brahmaputra River

Hydrologic data are the basic information that we need to successfully plan, design and operate any water resources development. Data are critically important for developing, calibrating, verifying and running the computer models. Data collection can be complex, expensive and time consuming. The availability of a common database would be a great saving to a Nation (Fan, 1998).

Sediment data helps in providing historical record of chemical conditions of the environmental system, identifying sources and sinks of pollutants, assessing their fate and potential effects, inferring their availability, estimating geochemical cycles and formulating transport model (Horowitz, 1985). Without proper source identification, wastage of resources may occur for adopting sediment control measures at wrong places (e.g. taking control measures to reduce surface erosion when channel and gully erosion are the main sources of sediments) (Walling, 2005). Characterization of surface water suspended matters is a necessary first step in determining the role they play in the transport of pollutants (Hiller, 2001).

The rivers of Asia and the Pacific Islands contribute 35% of the river flow and 50-70% of the total sediment delivered by all rivers to the oceans (Milliman and Meade, 1983; Hu et al., 1998). However, very few Asian rivers have been investigated in detail so far, the Brahmaputra perhaps the least. Only brief reports have appeared about the part of the river falling in India, based on very few samples (often only one or two) of the water chemistry (Subramanian, 1979; Hu Ming-Hui et al., 1982; Sarin and Krishnaswami, 1984; Sarin et al., 1989), sediment characteristics (Subramanian, 1980; Goswami, 1985) and heavy metal concentrations in sediments (Subramanian et al., 1987). In recent years, Datta and Subramanian (1997, 1998) and Datta et al. (1999) have studied texture, mineralogy and sediment biogeochemistry of the Ganges-Brahmaputra-Meghna system as a whole in Bangladesh.

Many hydropower schemes are under planning/investigation in the upstream areas of the study location and some are being installed (Jain et al., 2007). The data generated here may be used for estimating the changes in sediment behaviour after installation of the hydropower schemes. Major dams currently harness main rivers on all continents (Dynesius and Nilsson, 1994; Vorosmarty et al., 1997b) and store 90-99% of the incoming sediments (Vorosmarty et al., 1997a) (cited from Meybeck, 2001). Drastic reduction in total suspended loads is observed in all dammed rivers (e.g., Colorado, Columbia, Mississippi, Rio Grande, Nile, Zambezi and Indus. The Huang He, once a perennial river, is now drying up during summer period due to diversion of its water to reservoirs (Meybeck, 2001). According to Kondolf (1997), dramatic reduction in sediment supply downstream of impoundments leads to “hungry waters” whereby the river compensates for the reduced load by downcutting and lateral erosion.

Sharma (2002) has recommended initiation of sediment studies with extensive network in the Ganga and Brahmaputra basins. As these basins are so far less influenced by construction of reservoirs, these are ideal areas for the studies of natural sediment yield characteristics in South Asia. These studies will also help in better implementation of the various projects and schemes planned for the region. More than 150 hydropower projects are proposed to be installed in the upstream of the Brahmaputra River for generating 60000 MW of power. Although most of these will be run-of-the river projects, there will be impact on sediment transport downstream.

1.12. Objectives of the present study

The main objective of this study was to characterize the sediments in the

Brahmaputra River and to explore interrelationships among some of the measured parameters. The nature of this study resembles more to baseline studies than to regular monitoring (Manly, 2009). This study might serve as a document of the present status of sediments in the river for ascertaining any changes in the future due to various anthropogenic activities, like installations of a number of proposed hydro-projects in the river basin. Since no comprehensive study was carried out before the current one, it could have been difficult to ascertain the change in sediment flux due to this major human impact. The present study is expected to provide important baseline for studying comparative sediment fluxes in the future. Moreover, the current study is possibly one last opportunity to study natural sediment transport in the Brahmaputra Basin and their characterization as growing human impact has been witnessed on the river in recent times. Brief descriptions of various components of the study have been given below.

1.12.1. Analyses of discharge and suspended sediment characteristics

This part consists of studying temporal (daily, monthly and seasonal) variations of discharge (Q) and suspended sediment concentrations (C) and C-Q relationship, cross-sectional variations of ‘C’, and estimating total sediment load transported by the River. These studies help in identifying sediment provenance (Williams, 1989) and setting up monitoring strategies (Meybeck, 2001).

1.12.2. Particle size studies

Particle size characteristics of the sediments throw light on provenance (Weltje and Prins, 2007), transportation dynamics (deposition / resuspension) (Singh et al., 2007), and pollutant adsorption potential (Fontaine et al., 2000) of sediments in a river. Particle size characteristics were studied to have better idea on these aspects.

1.12.3. Mineralogical studies

Sediments retain their mineralogical signatures from their sources up to the delta region (Heroy et al., 2003). Mineralogical data help to identify and to differentiate sediment provenances and transfer pathways (Xu et al., 2009). Extent of erosion of turbine components (Bajracharya et al., 2008) and adsorption capacity of pollutants largely depend on mineralogy of the sediments (Jha et al., 1990). Mineralogical studies were carried out to gain knowledge on such aspects of the sediments.

1.12.4. Analyses of morphology and chemical composition

Morphology and composition of the sediment particles gives an idea of their provenance and maturity, basin geology, weathering and erosion patterns prevalent in the river basin (Sholkovitz et al., 1978; Martinelli et al., 1993; Manjunatha et al., 1996; Singh and France-Lanord, 2002; Pokrovsky et al., 2005). Scanning Electron Microscope equipped with Energy Dispersive X-Ray Spectroscopy was used for studying morphology and composition of the sediments as an effort to understand these aspects.

1.12.5. Analyses of metals in the sediments

Mobility of sediment-associated metals and their bioavailability in aquatic environment depends on the geochemical partitioning of the metals within the sediments (Tessier et al., 1979) and the properties of the aquatic environment (Stumm and Morgan, 1996; Warren and Haack, 2001; Eby, 2004). Metals forming part of the crystal lattices are not likely to be released under normal geochemical fluctuations (Tessier et al., 1979). Therefore, only the extractable metals (ASTM, 2003) in the sediments were determined using Atomic Adsorption Spectrophotometer for assessment of its pollution potential.

1.13. A note on the data used in the thesis

There are two kinds of data in the thesis: one generated by the researcher and the other obtained from Central Water Commission (CWC). Chapters 4 and 5 contain both these data, and to distinguish one from the other, the data collected by the researcher have been referred to as 'Top Water Layer Suspended Sediment' (TWLSS). Chapters 6 and 7 are based entirely on the data collected by the researcher. It is worth mentioning here that CWC data were purchased from the Middle Brahmaputra Division of CWC, Government of India.

It may be pertinent to point out here that CWC was the only possible source of these data since the State Water Resource Department, Assam, the only other organisation entrusted with the responsibility to generate data from the Brahmaputra River, did not have any discharge and sediment data for the period under report. Hence, there was also no further scope for supplementing the data used in the thesis.

CHAPTER 2

LITERATURE REVIEW

2. Introduction

Comprehensive suspended sediment data are essential for the calibration and validation of numerical models that aim to reproduce past soil erosion and sediment dynamics and to generate reliable data for management purposes (e.g., Mamede et al., 2006; Francke et al., 2008). On the other hand, systematically generated sediment data, particularly for large rivers, are yet to be available adequately (Xu, 2000). This is mainly due to the fact that sediment data measurement involves considerable difficulty and expense. Automated measurement system is necessary for recording temporal variability of sediment flow and for getting rid of some of the demerits (e.g., alteration of particle size characteristics in ex-situ analysis) associated with traditional forms (collecting and then transporting to laboratory) of sediment measurements. Streams carry more than 50% of their total sediment transport during flood events (Nelson and Benedict, 1950) and as their occurrences are unpredictable, automated measurement becomes useful. Time and labour involved in sediment sampling also increase the expense (Wren et al., 2000).

The ideal procedure for measurement of suspended sediment concentration (SSC) and particle size distribution (PSD) is to measure these at all points in a given river or stream. The second best procedure would be to measure at all points in a cross section. The third and fourth ranked possibilities are measuring along one vertical or measuring at one point, respectively (Wren et al., 2000).

2.1. Sediment quantity

2.1.1. Sediment yield

Existing model for sediment yield vary greatly in complexity from simple regression relationships to complex physically based distributed simulation models. The regression relationships link variation in sediment yield to climatic and physiographic characteristics (Table 2.1). The examples for these include the Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978) and Revised Universal Soil Loss Equation, RUSLE (Renard et al., 1991). The physically based models attempt to provide realistic representation of the process operating in small constituent areas of the catchment. These include the ANSWERS model (Beasley et al., 1980) and AGNPS models (Young et al., 1987). In these models, response of the catchment is routed to its outlet for simulating the detailed record of sediment load during the storm events.

Janssen and Painter (1974) developed linear regression models relating average annual suspended sediment yield of 79 catchments greater than 5000 km^2 (UNESCO, 1967; Holman, 1968) with a number of climatic and topographic variables (Discharge, basin area, altitude, relief length ratio, precipitation, temperature, vegetation and "proneness to erosion" parameter). The models were useful for predicting the scale of the sediment problem in rivers where no sediment data existed. Estimate of the annual global denudation (26.7 x 10^9 tons/year), based on the models, compared well with existing figures. Sediment yield correlated positively with runoff, altitude, relief, precipitation, temperature and rock softness, and negatively with area and protective vegetation.

Dunne (1979) examined the influence of land use on sediment yield in 61 Kenyan (tropical) catchments by regression analyses on field data. Inclusion of land use variables in the model yielded R^2 value as 0.77, and their exclusion decreased R^2 to 0.11. He concluded that land-use could not be ignored in the construction of global or regional analyses of erosion rates.

Kothiyari (1998) showed that prediction of temporal variation and total sediment yield can be done using methods based on time-area segmentation of a catchment. He also outlined the potential for application of Geographical Information System (GIS) analysis in predicting the distribution of soil erosion over the catchment.

Ludwig and Probst (1998) stated that following was the best model to describe the sediment fluxes globally:

$$\mathbf{sF_{TSS} = 0.020\ (Q \times Slope \times Four)}$$

$$n = 58,\ r = 0.91,\ P < 0.0001$$

[sF_{TSS} (sediment yield) in t km^{-2} yr^{-1}, Q (mean annual runoff intensity) and Four (seasonal precipitation variability) in mm, and slope in radian.]

When applied to a total continental area (exoreic and ice-free), the model resulted in an average global sediment yield of 139.4 t km^{-2} yr^{-1}. The total sediment came out to be 14.80 Gt/yr.

Table 2.1: Some models for sediment yield prediction (Ludwig and Probst, 1998)

Sl No	Study	Parameters used for sediment yield prediction	Global (Regional) F_{TSS} (Gt/YR)
1	Langbein and Scumm, 1958	APPT	10.8
2	Douglas, 1967	APPT	11.5
3	Wilson, 1973	APPT	19.3
4	Ohmori, 1983	APPT	56.6
5	Fournier, 1960	Four, Relief	64.0
6	Pinet and Souriau, 1988	Elev, Orogeny type	16.2
7	Ahnert, 1970	LR	9.3
8	Jansen and Painter, 1974	Q, A, Elev, Slope, AT, LithMI, VegI	26.7
9	Probst, 1992 (Model-I)	Slope, Q, APPT, VegI	22.9
10	Probst, 1992 (Model-II)	Slope, LithMI, APPT, Q, VegI	21.7
11	Ludwig and Probst, 1998	Q, Slope, Four	14.8

[APPT=Annual precipitation total (mm), Four=Seasonal precipitation variability, LR=Local Relief (m), Q=Mean annual run-off intensity, A=Drainage Area, Elev=Modal basin elevation (m), AT=Annual temperature mean (°C), LithMI=mechanical erodibility index of lithology, VegI=Index of soil protection capacity of vegetation]

Earthquake is a dominant controlling variable for sediment yield. The 1950 earthquake (Richter magnitude 8.7) changed the course and morphology of several Brahmaputra tributaries and introduced a large but unquantified volume of sediment via slope failure (Poddar, 1952, quoted by Goodbred Jr. et al., 2003). Goswami (1985, quoted by Goodbred Jr. et al., 2003) showed that the sediment rating (sediment load/ discharge) of the Brahmaputra River had increased dramatically soon after the earthquake (1955-1960) and was about an order of magnitude higher than when measured a decade later (1971-1976). He found that the channel aggraded 1.25 m from 1951 to 1971 and subsequently degraded 0.21 m from 1971 to 1976 in a 150-km-long reach of the Brahmaputra. He also noted several kilometers of channel widening during this time.

The dynamics of the Brahmaputra River was drastically affected in the late 20th century by abundant sediment supply to the upper reaches from numerous landslides caused by earthquake (EGIS, 1997; Goswami et al., 1999). Rapid aggradation of river bed occurred in the 1950s and 1960s in Assam, India, due to the earthquake-induced sediment supply, which reduced in the 1970s (Goswami, 1985).

Datta et al. (1999) reported that suspended sediments come mostly from resuspension of bed sediments and bank scour during high flows in the Brahmaputra River.

Restrepo et al. (2006) examined sediment yield and its response to control variables in the Magdalena drainage basin (Colombia, South America) based on a multi-year dataset of sediment loads from 32 tributary catchments. Sediment yield varied from 128 to 2200 t km^{-2} yr^{-1} (mean ~ 690 t km^{-2} yr^{-1}) for catchments ranging from 320 to 59,600 km^{2}. Mean annual runoff was the dominant control and explained 51% of the observed variance in sediment yield. A multiple regression model, including two control variables, runoff and maximum water discharge, explained 58% of the variance. The model efficiency was 0.89 indicating its robustness for predicting total sediment yield from tributary catchments in the Magdalena basin. Within the spatially distributed models, runoff, precipitation, precipitation peakedness, mean elevation, mean water discharge, and relief were the major control variables.

Vanacker et al. (2007) studied the spatial variation in suspended sediment concentration in the catchment of the Paute River (Southern Ecuador) system in relation to climate, lithology, topography and land use. They observed highest suspended sediment load in those catchments where major landslides were present and human disturbance was minimal. They were of the opinion that natural geomorphic processes (e.g. landslides) might contribute significantly to sediment load.

Mathematically, computer model is not a true representation of reality, but at best, only an approximation of the solution to the problem. An expert's interpretations of computer outputs are often required for a successful application of the models (Fan, 1998). In his keynote lecture in the Seventh International Symposium on River Sedimentation, Raudviki (1998) said that knowledge of the physics of loose boundary processes was much limited in comparison to the sophistication of the numerical techniques developed to model these. Many processes in loose boundary hydraulics have not yet been defined by functional relationship which is essential for mathematical modelling. Modellers often produce plausible results with assumed relationship. It is a matter of concern that much of available research talent is moved to the field of numerical modeling. According to him, this will benefit neither the Computer Science nor the physics of loose boundary processes. He regrets that very few people in the world are involved with the research of the physics of this complex and fascinating subject.

2.1.2. Sediment load

Researchers have developed a series of statistical techniques (e.g., rating curves, interpolation, ratio estimators, planning level load estimators) to estimate sediment loads based on discrete sampling (e.g., Walling, 1977; Williams, 1979; Phillips et al., 1999; Quilbe et al., 2006).

The rating curve method describes the average relation between discharge (Q) and suspended solids concentration (SSC) (Horowitz, 2003), although it may not be applicable to highly dynamic fluvial environments because of the high scatter of data and the consequent poor relationship between Q and SSC nor to catchments experiencing wide ranges of sediment concentrations. Interpolation techniques have been used frequently to overcome these statistical problems (e.g., Phillips et al., 1999), as well as to derive continuous sedigraphs from real SSC data. One way to deal with these methodological issues is the use of turbidity probes (e.g., optical backscatter type) to obtain continuous records of water turbidity as a surrogate measurement of SSC. However, Thomas (1985) has outlined the problems (calibration, high cost, frequent breakdown of instrument, necessity of 120-volt ac electrical power) associated with the method based on turbidity. He has recommended continuous measurement of discharge and occasional measurement of suspended sediment concentration for estimation of sediment load. According to him, time of measurement, method of estimating the yield and the properties of the estimate are important regardless of the method of sampling (manual or with automatic sampling equipment). Despite large uncertainties in planning level load estimation, it is widely used as a first estimation of pollutant loads (Schwartz and Naiman, 1999) due to its simplicity.

Shimizu (1998) investigated the sediment load of Ishikari River (basin area= 14330 km^2), Japan, using existing data of water discharge, turbidity, suspended solids, grain size distribution of bed material, observed sediment transport rate. He observed a good correlation between turbidity data (collected continually every hour since 1975) and suspended sediment concentration, which can be expressed by,

$$C = 0.55\, D^{1.09}$$

where C=SS concentration (mg/L) and D=turbidity data measured by K-82S type automatic turbidity measurement device. The best fitting exponential equation which relates daily discharge data and sediment discharge of past 20 years for the river is as follows:

$$Q_s = 1.2 \times 10^{-7}\, Q^{1.83}$$

where Q=water discharge in m^3/sec and Q_s=sediment discharge in m^3/sec.

When continuous concentration data are not available due to cost, remoteness of sites or technical difficulties, the relation between water discharge and sediment concentration are obtained by least square regression using available data. This relation is used to find daily concentration values, and then to calculate any resulting load by summing (Quilbe et al., 2006; Charlton, 2008). Total sediment load passing the recording site for any day is calculated using the following relation (Charlton, 2008):

$$W_i = C_i \times Q_i \times 86400$$

where W_i = sediment load (kg), C_i = sediment concentration (mg/L), Q_i = water discharge (m^3/s), i = i[th] day of the year. The process is repeated for each day of the year to estimate the annual sediment load. The accuracy of these estimates is very much dependent on the range of flows that were sampled in deriving the relationship between discharge and concentration. The sediment load will be underestimated if flood flows are not included in the data used in the regression analysis (Charlton, 2008).

Sediment yield is controlled by the catchments and the rainfall characteristics at a site. Sediment rating curves may be used to estimate the sediment load to a reservoir. According to Asselman (2000), sediment rating curves do not account for variations of sediment supply due to seasonal effects, antecedent conditions, and differences in sediment availability at the beginning or the ending of a flood resulting in inaccuracies in predicted suspended sediment concentrations. These curves vary with site and seasons of the year. For example, the curve for March (non-monsoon period) may be entirely different from the curve for the month of August (Monsoon period). Different curves need to be developed for different sites and seasons for proper estimation of sediment yield (Garg, 2006).

WAPCOS (1993) recommended the following model for estimating sediment load for the Brahmaputra River at Pandu:

$$\mathbf{S_p = 5.046 \times 10^{-9}\, Q_p^{1.862}}$$

where S_p is the sediment load in metric tons for any month and Q_p is the monthly mean discharge in cumecs for that month (n = 98, correlation coefficient = 0.9650 and coefficient of determination = 0.9314).

When a bi-variate plot of discharge against suspended sediment concentration reveals a high degree of scatter, hysteresis loop is examined to explore the association between these variables (e.g., Wood, 1977 and Rieger et al., 1988). Hysteretic loops can be clockwise or counterclockwise. In natural catchments, these two types of hysteresis are explained by the relative position of sediment sources within the catchment in relation to surface runoff. In general, clockwise loops are caused by sediment accumulated near the catchment outlet, while counterclockwise loops are related to sources supplying sediment from remote places (Tarazon et al., 2009).

Tarazon et al. (2009) studied the sediment dynamics in the River Isábena [Aragon, Spain; 42°11'N, 0°20'E] through the analysis of hysteretic loops for the 73 floods with available sediment data. 57% of the analysed floods were counterclockwise, 37% were clockwise, and the remaining 6% did not show hysteresis. The average flood-suspended sediment concentration was 8 g/L, with maximum instantaneous values above 350 g/L. The high scatter between discharge and suspended sediment concentrations (up to five orders of magnitude) has not permitted the use of rating curve methods to estimate the total load. Interpolation techniques yielded a mean annual sediment load of 184,253 t y^{-1} for the study period, with a specific yield of 414 t km^{-2} y^{-1}.

Mossa (1996) observed that during high discharge years, suspended sediment concentration peaks preceded discharge crests by 40-85 days in the Mississippi River near Old River, LA, but the peaks coincided in low discharge years. Sediment peaks and discharge crests coincided downstream (near Belle Chasse, LA) regardless of flow magnitude. Generalization of relative timing of the sediment wave and flood wave and their downstream progression should be made with caution. According to him, these phenomena were influenced by local bed material and hydraulic conditions, and depended on the causative factors of sediment peaks.

Suspended fine sediment (<62 μm) in streams does not show sudden large fluctuations with time, but sand transport does (Wren et al., 2000). Burkham (1985) found coefficient of variation (COV) for high sand concentrations up to 70% for stream samples taken at 16 sites in five states of the USA. Willis and Bolton (1979) conducted an experiment under steady uniform flow in a laboratory flume with 0.5 mm sand. They observed average COV of 62% on sand concentration under various flows. Kuhnle and Willis (1998) also observed COV of about 100% for sand transport data from Goodwin Creek watershed in northern Mississippi. So, the COV may result from the variability of sand transport process in streams and rivers rather than due to error in the sampling techniques (Wren et al., 2000).

At their points of maximum suspended-sediment discharge, the Amazon transports an average of 1100-1300 x 10^6 tons per year and the Orinoco transports about 150 x 10^6 ($\pm$ 50 $\times$ 10^6) tons per year. Relations of sediment discharge to water discharge are complicated by unusual patterns of seasonal storage and remobilization, increased storage and reduced transport of sediment in the middle Orinoco during periods of peak water discharge, and storage of suspended sediment in the lower Amazon during rising discharge and re-suspension during falling discharge. Spatial distributions of suspended sediment in cross-sections of both rivers are typically heterogeneous, not only in the vertical sense but also in the lateral. The cross-channel mixing of tributary inputs into the main-stem waters is a slow process that requires several hundred kilometers of downriver transport to complete. Considerable fine-grained sediment is exchanged between rivers and floodplains by the combination of over-bank deposition and bank erosion (Meade, 1994).

Suspended sediment in the Amazon is not uniformly distributed with depth: the sand fraction (> 63 µm) of the suspended sediment is many times more concentrated near the river bed than at the water surface (Meade et al., 1979, pp. 17-25); even the suspended silt fraction (10-63 µm) is usually more concentrated nearer the river bed (Curtis et al., 1979; Meade, 1985, pp. 19-22). The difference between the calculated total sediment discharge and the measured suspended sediment discharge is called the "unmeasured load". Using the Modified Einstein Method, Posada and Nordin (1992) calculated that unmeasured loads in the main-stem Amazon and Orinoco Rivers varied from 2 to 15% of the measured sediment load, and averaged 6%.

Complete mixing of flows where two large rivers join requires a significant river length (Mackay, 1970; Krouse and Mackay, 1971; Stallard, 1987), which can often extend to tens or often even hundreds of kilometers (Cited by Parsons et al., 2008). Parsons et al. (2008) cited from Gaudet and Roy (1995) that upwelling of water at discordant-bed junctions reduced the downstream distance required for complete mixing from approximately 100 multiples of the channel width (W) to as little as 10 to 25W in small rivers.

Subramanian (1979) determined total suspended matter as 348 ppm, bed load as 674.83×10^9 kg yr^{-1} and denudation rate as 97.80×10^4 kg km^{-2} yr^{-1} for the Brahmaputra River based on samples collected at Guwahati during monsoon, 1977. He observed that entire annual load was carried during the monsoon period for some of the rivers of India.

Sarma (2005) reported that sediment load (COV = 0.85) was more variable than water discharge (COV = 0.15) in the Brahmaputra River during 1971-79.

Coleman (1969) summarized the discharge and the sediment transport of the Brahmaputra River at Bahadurabad as shown in Table 2.2 which showed that sediment transport increased with discharge. He mentioned that flowage failure of river banks during falling stages of water (Coleman, 1969) might keep the sediment concentration from reducing with discharge for some days as manifested by the Q-S curve in a falling stage of hydrograph. However, figure-8 type hysteresis (Williams, 1989) results in the plot of discharge versus sediment load provided in Table 2.2 (Appendix-I).

Table 2.2: Hydrologic characteristics of the Brahmaputra River at Bahadurabad (Coleman, 1969)

Average monthly discharge (in 1,000 cusecs) (1956-1962)													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Max	233	176	211	304	849	1365	1602	1961	1713	1140	529	331	768
Min	154	120	133	182	282	936	1185	1085	853	497	300	200	635
Mean	184	153	165	252	629	1138	1418	1554	1248	759	374	235	678
Sediment transport (millions of tons) (1958-1962)													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Max	5.4	3.5	5.3	17.2	82.7	147.0	167.6	227.2	177.9	71.4	16.7	7.4	696.5
Min	2.4	1.6	2.2	5.4	13.0	58.9	104.4	108.8	72.1	23.2	10.0	4.0	530.9
Mean	4.0	2.5	3.6	9.7	36.4	87.6	121.6	163.3	117.8	42.9	12.1	5.4	607.7

Milliman and Syvitski (1992) compiled drainage basin areas, loads and calculated yields for 279 world rivers, 12 of which are reproduced in Table 2.3.

More recently, Boiten (2008) tabulated sediment transport of some of the rivers of the world (Table 2.4). He reported that the data contained in the table are highly approximate, and different sources may give variation up to factor 2 in sediment yield. Rivers in areas of temperate climates or with mild slopes generally carry small amounts of sediment. The Ganges and the Hwang Ho carry high amounts of sediment due to their catchments with strong relief covered with fine, erodible material.

Table 2.3 Drainage basin areas, loads and calculated yields for some world rivers (Milliman and Syvitski, 1992)

Sl No	River	Country	area ($\times 10^6$ km^2)	Average sediment Discharge (10^6 t / yr)	Yield (t / km^2 / yr)	Ref. Citation
1	Amazon	Amazon	6.10	1200	190	Meade et al., 1985
2	Hungho (Yellow)	China	0.77	1100	1400	Milliman and Meade, 1983
3	Brahmaputra	Bangladesh	0.61	540	890	Hossain, 1991
4	Ganges	Bangladesh	0.98	520	530	Hossain, 1991
5	Yangtze	China	1.90	480	250	Milliman and Meade, 1983
6	Irrawadi	Burma	0.43	260	620	Milliman and Meade, 1983
7	Magdalena	Columbia	0.24	220	920	Milliman and Meade, 1983
8	Mississippi	USA	3.30	210 (400)	120	Meade et al., 1990
9	Orinoco	Venezuela	0.99	150	150	Meade Pers. Comm.
10	Hungho (Red)	Vietnam	0.12	130	1100	Milliman and Meade, 1983
11	Mekong	Thailand	0.79	160	200	Milliman and Meade, 1983
12	Indus	Pakistan	0.97	59 (250)	260	Milliman et al., 1987

(Load value in parentheses indicates pre-dam values)

Table 2.4: Water discharge and sediment transport of ten rivers (Boiten, 2008)

Sl No	River	Catchment area Discharge (10^6 km^2)	Water discharge		Sediment transport		Sediment as ppm mg/L
			m^3/s	mm/ year	10^6 ton /year	mm/ year	
1	Congo	3.70	44000	370	70	0.015	50
2	Nile	2.90	3000	30	80	0.015	630
3	Wolga	1.50	8400	180	25	0.010	100
4	Niger	1.10	5700	160	40	0.025	220
5	Ganges	1.00	14000	440	1500	1.000	3600
6	Orinoco	0.95	25000	830	90	0.065	220
7	Mekong	0.80	15000	590	80	0.070	170
8	Hwang Ho	0.77	4000	160	1900	1.750	15000
9	Rhine	0.36	2200	190	0.72	0.001	10
10	Chao Phya	0.16	960	190	11	0.050	350

2.1.3. Effects of sediment yield

The economic significance of erosion and sediment yield are manifested “on-farm” in terms of reduced soil depth, diminishing fertility and declining crop productivity and “off-farm” in terms of channel and reservoir sedimentation and harbour siltation. Brown (1948) estimated the total economic cost associated with the downstream impact of eroded sediment in the United States as $175 million. Clark et al. (1985) estimated this cost to be $6100 million at 1980 values, of which $2200 million was attributed to sediment derived from the nation's (U.S.A.) cropland (Table 2.5). Canadian Standing Committee on Agriculture, Fisheries and Forestry (1984) estimated that soil degradation had been costing Canadian farmers about $1 billion per year. Brown (1984) estimated that the world's croplands were losing about 23 billion tons of soil in excess of new soil formation each year and consequently, the global soil resource was depleted by about 7% each decade (cited from Walling, 1988).

Table 2.5: The annual economic cost of sediment problems in the United States estimated by Clark et al. (1985) [From Walling, 1988]

Impact	Estimated Cost ($ × 10^6; 1980 base)	Cropland's share
In-stream effects		
Biological impacts	No estimate	
Recreation	2000	830
Water storage facilities	690	220
Navigation	560	180
Other uses	900	320
Subtotal	4200	1600
Off-stream effects		
Flood damage	770	250
Water-conveyance facilities	200	100
Water -treatment	100	30
Other uses	800	280
Subtotal	1900	660
Total (all effects)	6100	2260

Sediment deposition behind dams adversely affected capacities and functions of a large number of multi-purpose, irrigation and power reservoirs in India (Table 2.6). The actual rate of siltation was many times more than the rate initially assumed. In 36 years, the Nizamsagar faced 97.11% loss in dead storage and 44.87% loss in live storage due to sediment deposition (Gupta, 1981).

The 35 reservoirs in Taiwan assume the vital functions of providing public water, irrigation water, and generating hydroelectric power (Hsu and Hsieh, 1998). Weak geology, steep topography, and high precipitation have resulted in a combined annual sedimentation rate of 14600000 m^3 for all the 35 reservoirs in Taiwan (Hsu and Hsieh, 1998). As new projects face strong resistance from the public, preservation of existing reservoir capacity by mechanical excavation, dredging (hydraulic/mechanical) and hydraulic flushing have been adopted in Taiwan. Unit dredging cost in 1996 was NT$ 50/m^3 (1 NT$ ~ $0.029) (Hsu and Hsieh, 1998). Fan (1998) reported that out of 505 reservoirs surveyed in the US, 134 (26.5%) had sedimentation problems.

Table 2.6: Sediment data of selected reservoirs (India) [Gupta, 1981]

Sl No	Reservoir	CA	AARS	ARS		Remarks
				A	O	
1	Bhakra Nangal	21960	28395	90	129.0	Capacity survey every year
2	Hirakud	31900	27307	53	85.6	Inflow-Outflow method
3	Maithon	2010	5980	34	300.0	Capacity survey in 1963 & 1965
4	Panchet	3790	8580	52	226.0	Capacity survey in 1962, 1964 & 1966
5	Machkund	755	498	82	66.0	Inflow-Outflow method
6	Tungabhadra	10735	41058	90	382.0	Capacity survey in 1963
7	Mayurakshi *	692	2387	75	345.0	Capacity survey in 1965 & 1970
8	Ramganga	1157	4479	90	387.0	Sediment inflow data
9	Beas Unit-II	2635	7905	90	300.0	Sediment inflow data
10	Matatila	7955	7358	30	92.0	Inflow-Outflow method
11	Nizamsagar**	7152	9840	6	137.5	Last capacity survey in 1967
12	Ukai	24025	55528	31	230.0	Inflow-Outflow method

[CA = Net catchment areas in square miles; AARS = Annual average rate of silting (acre.ft); ARS = Annual rate of silting (acre.ft per 100 square miles); A = Assumed; O = Observed; *The sediment rate for the period 1965-70 (5 years) is 478 Acre.ft/100 sq. miles/year; **The sediment rate during 1962-66 is 268 Acre.ft/100 sq. miles/year.]

Heavy sediment load and high rainfall occurring within a short period in the year give rise to floods in the Brahmaputra Basin. Floods created havoc in Assam (India) during last few years. Severe floods occurred in 1987, 1988, 1992 and 1995. The entire embankment system was put to maximum strain resulting in 102 breaches and cuts in 1987 and 220 in 1988. A tentative assessment of flood damage in Assam during 1953-1995 periods is shown in Table 2.7.

Table 2.7: Tentative assessment of flood damage in Assam (1953-95) (Jain et al., 2007)

Theme	Total	Maximum
Area affected in million hectares	41.66	3.82
Population affected in million	98.10	10.47
Damage to crops in million hectares	5.08	1.13
Loss to crops in terms of crores of rupees	3288.31	334.1
Damage to houses - numbers	3327189	4998
Damage to house - value in terms of rupees (crores)	296.80	103.92
Cattle lost	431537	108913
Human lives lost	1724	226
Damage to public utilities in rupees (crores)	832.42	225.82
Total damage to crops, houses and public utilities (million rupees)	44175.30	6638.40

[Population affected and cattle lost were maximum in 1987. The other maxima occurred in 1988.]

Braiding of the Brahmaputra River is a result of huge sediment supply from its catchments. Takagi et al. (2007) analyzed spatial and temporal changes in the large, sandy, braided system of the Brahmaputra River, Bangladesh, using satellite images and GIS. The basic data used in the study were satellite remote sensing images for 14 different years between 1967 and 2002. According to them, the Brahmaputra River systems went through four geomorphological phases during the study period with different spatial distributions of landforms, land cover, and temporal changes: 1) the late 1960s to early 1970s, 2) the mid-1970s to early 1980s, 3) the mid-1980s to early 1990s, and 4) the mid-1990s to early 2000s. Phases 1 and 3 exhibited more complex river conditions, phase 2 indicated quasi-dynamic equilibrium and phase 4 suggested a state of dynamic equilibrium. The conditions that prevailed in phase 1 were related to the prolonged effect of earthquake-induced sediment supply. They found that the maximum width of the braid bars was always about 16 km, the mean increased with time from ca. 9 to 11 km, and the minimum width changed from ca. 3 km (until 1980) to a constant of ca. 7 to 8 km in the early 1990s. They also observed frequent occurrence of channels more than 2 km wide between 1967 and 1992, but rarely after 1994. Coleman (1969) also described wide channels in the mid-1960s.

2.2. Grain size studies

Particle size distribution analysis can aid in designing treatment processes, making decisions about changes in operations, and/or determining process efficiency (Standard Methods, 2005). Transport and deposition behaviour of suspended sediments under various conditions (e.g., storm waves, oceanic currents) are governed by particle size to a large extent. Information on grain size distribution of suspended sediments is limited (Bogen, 1992). As large rivers play an important role in controlling the physical and biogeochemical features of estuaries and ocean margins (McKee et al, 2004; Meybeck et al., 2006; Bianchi and Allison, 2009), studies of their sediment characteristics are necessary.

2.2.1. Usefulness of grain size studies

Awasthi (1970) reported that the sign of skewness could act as an indicator of energy condition prevailing in the depositional medium of terrigenous sediment. He stated that negative skewness was a characteristic of turbulent energy conditions and positive skewness pointed to a calm and steady energy environment of sedimentation. However, Teleki and Weggel (1972) warned that the conclusions presented by Awasthi (1970) were based upon erroneous hydraulic concepts.

Studies related to suspended sediment transport by rivers become problematic as only small amounts of sediments can be extracted from river water and most of the analyses require several grams of sediments. In such cases, grain size analysis may be used as a tracer for identification of sediment provenance as modern laser particle size analyzers are capable of analyzing low concentration samples (Kurasighe and Fusejima, 1997).

Stummeyer et al. (2002) used content of quartz as an indicator for the grain size distribution of the sample material, because the limited amount of suspended matter samples did not allow grain size analysis. Many researchers have analyzed grain size distribution to characterize sediments (Buller and McManus, 1972, 1973; Duck, 1994; Machida et al., 1975).

Singh et al. (2007) reported that cumulative size distribution curves might give an idea of the transportation dynamics of sediments in a river. They found that nearly 20% of the bed load of the Ganga River moved as bed load and the rest 80% moved in suspension. This phenomenon was reflected by overlapping of the coarsest parts of the cumulative curves for bed and suspended sediments. They observed that all the cumulative grain size curves for the bed load sediments showed distinct “break” in slope, which represented the maximum grain size transportable in suspension at maximum shear stress.

Frequent and costly dredging operations become necessary to address the problem of silting up of harbours and channels. Knowledge of transport directions of sediments is useful in planning the location and layout of new harbours, construction of groynes or other structures to control sedimentation at existing facilities or possible dispersal patterns of contaminants adsorbed to sediments. Various studies have related grain size trends (spatial variation of grain size parameters within the same environment) to net sediment transport (Miller et al., 1977; Komar and Reimers, 1978; Mclaren, 1981; McLaren and Bowles, 1985, 1991; Gao and Collins, 1992). So, sediment transport patterns within different environment may be inferred using the grain size trends. Trend vectors to a central sampling station are defined based on mean grain size, sorting coefficient (standard deviation) and skewness. These vectors are summed up to produce a resultant. This is done for each sampling station and the resultant vectors are compared to decide transport direction. There are computer programs to do the trend analysis for defining net sediment transport pathways (Gao, 1996; Chang et al., 2001). Roux et al. (2002) have cautioned that observed transport directions from computer programs should be compared with additional information on the dispersal patterns and if no such information is available, the trend type producing the highest vector magnitude should be employed.

Ex-situ analyses may not represent field-conditions. Aggregates of sediments are often broken up in sample collection and handling. Again, allowing the particles to settle may create more aggregates than existed in the original sample (Wren et al., 2000). Researchers emphasize the importance of measuring particle sizes for fine sediments without disturbing aggregates (Walling and Moorhead, 1989; Droppo and Ongley, 1992, 1994; Woodward and Walling, 1992; Walling and Woodward, 1993). Phillips and Walling (1995) recommended in-situ measurements of fines in suspended sediment as they observed increases in volume mean particle size up to 24% in an experiment of settling for 1 hour followed by resuspension.

2.2.2. Some examples of grain size studies

Siddiquie (1967) studied the sediments of the Bay of Bengal for various particle size parameters. He observed that the median diameters of the sediments ranged from 0.74 µm to 700 µm. Coefficient of sorting varied from 1.75 to 10.69. Most of the sediments were normally sorted (coefficient of sorting varying from 2.5 o 4.5), few samples were well sorted and about a third was poorly sorted. Skewness ranged from 0.027 to 8.81. Most of the sediment samples exhibited positive skewness, suggesting predominance of coarser admixture. Kurtosis ranged from 0.02 to 0.34.

Kanjilal et al. (1970) studied the sedimentary parameters of Ganga sands. The sands were medium to very fine size, moderately to very well-sorted with negative to very positive skewness and platykurtic to very leptokurtic. Majority of the sediments were bimodal and according to them, this was due to the presence of considerable amount of silt.

In the particle size analysis of the Nile River suspended sediments, Shalash (1982) observed that, as a result of increase in suspended sediment concentration, the percentage of fine sand (0.2-0.02 mm) decreased, the percentage of clay (<0.002 mm) remained constant and was not affected, but the percentage of silt (0.02-0.002 mm) increased. He reported that presence of coarse sand (>0.2 mm) in suspended sediment was negligible.

Singh and France-Lanord (2002) studied the grain size of the Brahmaputra sediments (suspended) collected during post-monsoon (October, 1999) and the pre-monsoon season (July, 2000) at Dibrugarh, Tezpur, Guwahati and Dhubri. They observed that the sediments consisted mostly of silts with clay fractions (< 2 μm) representing 0.5-3% of the total sediments.

Based on the fact that silt is a major component of most continental margin sediments, Gorsline (1985) reported that silt was the dominant class among the fine-grained textural classes.

2.3. Mineralogy

Mineralogical studies help in tracing sources of sediments (Johnson et al., 1985; Uddin and Lundberg, 1998) and understanding past weathering regimes induced by changing climatic conditions (Debrabant et al., 1993; Derry and France-Lanord, 1996). According to Guyot et al. (2007), clay minerals contain information of suspended sediment maturity, weathering intensity and source area. Identification and characterization of clay minerals can help in understanding the likely nature and mechanisms of active erosion processes, and can be useful in flood mitigation and management approaches in flood prone areas like the Brahmaputra valley (Kotoky et al., 2006).

Subramanian (1979) reported that the Ganges and the Brahmaputra carried a very large amount of quartz and feldspars because of high coarse suspended silt in the rivers, while the very fine-sized suspension of the Cauvery River contained mostly clays. He reported that mineralogy of suspended particles is likely to be governed by size characteristics of the sediments.

Subramanian (1980) studied the mineralogy of some Indian rivers. He reported that the suspended sediments of the Brahmaputra River contained about 11% feldspar, 17% quartz, 26% kaolinite, 2% amphibole, 22% illite and 22% chlorite and no mixed-layer clays or montmorillonite. He observed that Himalayan rivers were characterized by the presence of large amounts of illite, equal quantities of kaolinite (7 Å) and chlorite (measured at 4.72 Å, Biscaye, 1965), and little or no mixed-layer clays and montmorillonite The four southern rivers (Mahanadi, Godavari, Krishna and Cauvery) were characterised by the absence of chlorite, abundance of montmorillonite, presence of trace quantities of mixed-layer clays and small quantities of both mixed-layer clays and illite. The central Indian rivers (Narmada and Tapti) had mineralogical characteristics between those of the southerly and the Himalayan drainage systems (Subramanian, 1980).

Sarin et al. (1989) reported 62.5% illite, 18.8% kaolinite, 18.8% chlorite but no smectite in the bed sediments of the Brahmaputra River at Guwahati.

Singh and France-Lanord (2002) found primary minerals (quartz, muscovite, feldspars, biotite) to be dominant in the Brahmaputra sediments. X-Ray diffraction data revealed the presence of illite, vermiculite and chlorites in the clay fractions, but no detectable proportion of kaolinite or smectite. They observed lower carbonate content (not exceeding 0.6%) in the Brahmaputra sediments (e.g., 0.6% at Dibrugarh, which reduced downstream to 0.1% at Tezpur) compared to the Ganges sediments (4-7%). They stated that strong dissolution due to high rainfall might lead to this low carbonate value.

Mahanta and Subramanian (2004) observed the dominance of quartz (45.23±9.75 %), feldspar (20.38±9.70 %) and clays (30.38±13.25 %) in the suspended sediments of the Brahmaputra River collected at 13 locations covering the entire length of the river within Assam, India. They reported that the suspended sediments (<2 μm) consisted of chlorite (30.85±8.91 %), illite (40.38±16.67 %) and kaolinite (26.85±8.31 %) with occasional exceptions of montmorillonite (2% in 3 samples and 9% in 1 sample out of 13 samples). They found illite as the dominant clay mineral in the upstream. They reported very low quantity of carbonate minerals (6.55±4.52 %). According to them, predominant physical weathering of granitic and metamorphic rocks in the cold and dry climate of the Tibetan Plateau resulted in the formation of large amount of illites. They cited Raymahasay (1970) as suggesting 9:1 as the ratio between mechanical to chemical erosion in the Brahmaputra basin.

Kotoky et al. (2006) analysed bed sediments of the Brahmaputra River collected along stretches of the river near Majuli Island and Kaziranga National Park. They reported dominance of kaolinite with subordinate amount of illite and chlorite in the clay fraction (≤ 3.9 µm) of the sediment. They also reported presence of albite in the bed sediments of the river. They stated that heterogeneity in natural samples might affect identification of smaller fractions of mineral species in the samples. Presence of high iron content in chlorite was also reported in their findings.

Gupta (1961) reported that the mineral assemblages derived from Himalayan region were characterised by abundant illite and chlorite. According to Sen and Chatterjee (1960), illite was the predominant clay mineral in Ganges monsoon silt, a product of mechanical weathering dominant in the Himalayan region (cited by Rama Murthy and Srivastava, 1979).

Chakrapani et al. (1995) reported that suspended sediments of the Ganges River contained mica as the dominant mineral followed by chlorite, vermiculite, kaolinite and smectite. He observed that mica content decreased and smectite content increased downstream with no variation for other minerals.

Two types of mineral associations, viz., smectite and kaolinite (SK) and illite and chlorite (IC), were reported by various studies for Neogene and Early Pleistocene Bengal Fan sediments (Brass and Raman, 1990; Debrabant et al., 1993; Derry and France-Lanord, 1996). According to these studies, IC is associated with high sediment fluxes and periods of physical weathering and Himalayan uplift, while SK is associated with periods of chemical weathering and tectonic relaxation. From isotopic (Sr, Nd, O and H) studies, France-Lanord et al. (1993) suggested that the majority of the smectite in the Ganges forms from low temperature alteration of the High Himalayan Crystalline metasedimentary series (HHC) sediments from pedogenic processes in the Indo-Gangetic floodplains, while IC forms from direct physical erosion of the HHC (cited by Heroy et al., 2003).

Rao et al. (1988), Kolla and Rao (1990), Segall and Kuehl (1992) and Wijayananda and Cronan (1994) reported that illite was the dominant clay mineral in the northeast Bay of Bengal, where the Ganges-Brahmaputra river system discharges its total sediment load carried down from the Himalayan sedimentary rocks. They also observed a relatively high amount of smectite in sediments derived from the crystalline rocks of peninsular India, whose abundance increased gradually from the Bay of Bengal towards peninsular India (cited by Datta and Subramanian, 1997).

Siddiquie (1967) studied the sediments of the Bay of Bengal for clay mineralogy. He found that the diffractograms of the samples showed reflections at about 10 Å (varying between 9.8 and 10.3 Å) and 7 Å (varying between 7.07 and 7.24 Å) indicating the presence of illite and kaolinite. Illite ranged from 50-80% while kaolinite varied from 15-34%. Montmorillonite was generally 2-4% and presence of chlorite was found in only

1 sample (21%). According to him, these minerals were derived from the peninsula and Himalayas where they occurred abundantly in sedimentary rocks and soils of the river basins supplying the sediments to the Bay.

Huizing (1971) studied the mineralogical composition of the sand fractions of floodplain deposits of the Brahmaputra, Ganges, Meghna, Tista and some other small rivers of East Pakistan (Bangladesh). He found that the sand fractions contained high amounts of feldspars, micas and amphiboles. He conjectured that these minerals might have been derived from crystalline rocks in the Himalayas.

Mallik (1976) observed illite, kaolinite and chlorite in the Ganges and Brahmaputra delta sediments, and montmorillonite along the east coast (Godavari-Krishna) sediments.

Datta and Subramanian (1997) observed abundance of detrital minerals (quartz and feldspar) in the Bengal basin (Ganga-Brahmaputra-Meghna river system) sediments and attributed the results to its source in one of the youngest mountain ranges of the world and to the drainage areas of the river system, which is rich in Quaternary floodplain deposits. The clay minerals in the <4 µm fraction of the bed sediments consisted of 90% illite and kaolinite (in almost equal proportions), 10% chlorite and very low amounts of montmorillonite. They cited various references to explain this mineral assemblage in the GBM river system: a) Richness of illite due to dominance of muscovite type mica in the source rocks (Griffin et al., 1968; Segall and Kuehl, 1992) and neotectonic activity in the basin (Morgan and McIntire, 1959; Valdiya, 1984; Pant and Sharma, 1993); b) Kaolinite from the floodplain (Brinkman, 1977; Islam and Lotse, 1986) experiencing intense soil-forming processes (kaolinization) (Griffin et al., 1968); c) low chlorite due to its lesser stability in lowland tropical areas (Irion, 1991). The negligible amount of montmorillonite was attributed to scarcity of eruptive igneous rocks in the drainage basin. They stated that higher amount (17-37%) of clay minerals in the suspended sediments (bed sediment values: 3-32%) was due to grain size effect on the mineral composition, and insignificant amount of carbonate minerals was due to differential settling of detrital carbonates in the upper reaches during transportation. They further commented that the amount of illite in the Bengal Basin sediments is similar to the values (between 45% and 60%) for the world river bed sediments (cited from Irion, 1991).

Heroy et al. (2003) conducted mineralogical analyses on borehole (up to 90 m) and surficial sediment grab samples collected in the Bengal Basin. They found that Smectite is high in the Ganges (~39%) and low in the Brahmaputra (~3%). The Brahmaputra sediments contained more kaolinite (29% vs 18%), more illite (63% vs 41%), and more chlorite (3% vs 1%). Their results for Epidote/Garnet ratios (>1 for the Brahmaputra and <1 for the Ganges) were similar to those determined by Huizing (1971). Based on the characteristic properties (E/G ratios) of sediments of these rivers and clay mineralogy (IC-SK associations), they opined that their results suggested active river switching and Quaternary climate change.

Soil (<2 μm) samples in the old Brahmaputra flood plain showed abundance of illite and considerable amounts of chlorite and vermiculite (some partially chloritized). Ganga floodplain samples showed dominance of illite, and smectite up to one-third of total clay minerals (Egashira et al., 2004).

Rama Murthy and Srivastava (1979) observed a high percentage of quartz in the shelf sediment of the Bay of Bengal. They ascribed this fact to resistance of quartz to weathering, which remained unaltered during weathering and transportation processes. Venkatarathnam and Biscaye (1977) reported that the Ganges--Brahmaputra river sources were primarily responsible for high percentages of quartz in the Bay of Bengal (cited by Rama Murthy and Srivastava, 1979).

Whetten and Kelley (1969) observed a downstream decrease of the ratio of quartz to all unstable constituents (feldspars, mafic, and lithic fragments) in the sediments of the Columbia River, whether the unstable constituents were taken individually or as a group,

Fayed (1970) observed abundance of montmorillonite and kaolinite in the Nile River Basin sediments. She stated that alkaline feldspars and the micas tend to alter to kaolin minerals, whereas ferromagnesian minerals, calcic feldspars and volcanic glasses commonly alter to members of the montmorillonite group. Development of montmorillonite minerals requires adequate supply of magnesium or ferric and ferrous ions in an alkaline environment containing necessary silica and alumina. Climatic factors and biotic ecology may modify this process (Fayed, 1970).

Martinelli et al. (1993) observed a downriver increase in quartz and kaolinite, and a decrease in the contents of Ca-plagioclase, Na-plagioclase and smectite-vermiculite. However, only illite displayed a conservative behavior. According to them, these changes were due to chemical and physical weathering of the sediment in its downward transport.

Guyot et al. (2007) studied the clay mineral composition of the Amazon River and reported that transportation, deposition, remobilization and tributary inputs changed clay mineral assemblages. They observed that lateral bank erosion introduced more mature sediments into the river, enriched in smectite.

In a study of the sediments of the Yukon River System, Eberl (2004) observed that approximately 3 wt% of the quartz, 15 wt% of the feldspar (1 wt% of the alkali and 25 wt% of the plagioclase), and 26 wt% of the carbonates (31 wt% of the calcite and 15 wt% of the dolomite) carried by the river dissolved in a reach of about 2000 km. He also observed changes in the mineralogies with seasons: during the summer of 2002, the quartz content varied by 20 wt% (minimum value in mid summer), clay mineralogy by 25 wt% (with maxima in mid July) and feldspar up to 10 wt%.

The weathering scale most commonly adopted is that of Stallard (1995) for mineral stability in tropical soils: Quartz >> K-Feldspar, Micas >> Na-Feldspar > Ca-Feldspar, Amphiboles > Pyroxenes > Dolomite > Calcite >> Pyrite, Gypsum, Anhydrite >> Halite (least stable) (Meybeck, 2003a).

Conversions of minerals take place in aquatic environments (Singh et al., 2005). Some reactions are given below:

$$\underset{\text{(Albite)}}{2NaAlSi_3O_8(s)} + 2H^+(aq) + H_2O(l) \longrightarrow \underset{\text{(Aluminosilicates)}}{Al_2Si_2O_5(OH)_4(s)} + 2Na^+(aq) + SiO_2(am)$$

$$\underset{\text{(Microcline)}}{2KAlSi_3O_8\,(s)} + 2H^+(aq) + H_2O(l) \longrightarrow \underset{\text{(Aluminosilicates)}}{Al_2Si_2O_5(OH)_4(s)} + 2K^+(aq) + SiO_2(am)$$

$$\underset{\text{(Aluminosilicates)}}{7Al_2Si_2O_5(OH)_4} + Mg^{2+}(aq) + 4SiO_2(am) \longrightarrow \underset{\text{(Smectites)}}{6[Al_2Si_3O_{10}(OH)_2]Mg} + 2H^+(aq) + 7H_2O(l)$$

According to Campos et al. (2008), smectite is formed through chemical weathering and its quantity increases when sediment sources contain volcanic rocks, and iIllite, chlorite and kaolinite mainly result from physical weathering of crystalline and low-grade metamorphic rocks.

Conflicting data on mineralogy of sediments of the same river may arise due to differences in the method of sampling, separation of grain size fractions, frequency and timing (season) of sampling and identification and estimation of the respective minerals (Datta and Subramanian, 1997).

2.4. Chemical composition

Studies on chemical composition of sedimentary material transported by rivers have considerably increased in recent decades due to increasing concern about chemical weathering and climate change (Gislason et al., 2006). Consumption of CO_2 by chemical weathering of silicate rocks over geological time was a significant factor in climate regulation (Berner et al., 1983; Dessert et al., 2003). Sediments act as a trap for different elements (Thomas et al., 1977); therefore, their metal concentrations may reflect the degree of pollution in an area (Edgren, 1987) (cited from Sabri et al., 1993). Potential bioaccumulation of some metals in living bodies through food chain is a major health concern. Regular monitoring of metals in aquatic environments is necessary (Peerzada et al., 1990) for adopting effective and timely control measures.

2.4.1. Elemental analyses

Sholkovitz et al. (1978) studied the major-element (Si, Al, Fe, K, Mg, Ca, Ti, Mn and P) composition of suspended matter of the Zaire River and Estuary using X-Ray Fluorescence (XRF). They found the suspended matter to be enriched in A1, Fe and P and depleted in Si, Ca, K and Mg relative to contemporary pelagic sediments and to suspended matter carried by the Amazon River. They stated that such enrichment and depletion were characteristics of soils in regions of intense chemical weathering.

Nesbitt and Young (1984) deduced from relative dissolution rates of K-feldspar and plagioclase, that CaO and Na_2O will be removed more quickly from weathered rocks than K_2O, tending to produce initial enrichment in potassium in residues of weathering (the source material for all sediments) (Cited by Hutcheon et al., 2000).

Subramanian et al. (1985) observed lower values of Al, Si and Ca, and higher values of Fe, Mn and Ni in the Brahmaputra sediments than those in the Ganges sediments. They ascribed this to the Brahmpautra sediments having mean grain size coarser than that of the Ganges sediments. They cited Subramanian (1979) and Milliman and Meade (1983) as reporting that world surface rocks (WSR) differed from the composition of sediments in Indian rivers in case of mobile and reactive elements due to dominant chemical weathering suffered by these sediments. Concentrations of Ca, Mg, Ba and Sr were lower for the Indian river sediments than those of WSR due to high carbonate equilibria in the waters of Indian rivers (Subramanian, 1983—cited by Subramanian et al., 1985).

Biksham and Subramanian (1988) observed a general increase of Mg, Al, Si, Cu, Zn, decrease of K and Ca, but no variations of Fe and Ti in the elemental compositions of Godavari River sediments. They opined that the large variations in the values of the elements emphasized the complexity of data generation on river sediments.

Ramesh et al. (1989) observed enrichment of minor elements (V, Cr, Co, Ni, Cu and Zn) in suspended sediments compared to bed sediments. They stated that similar observations were reported for several other major rivers such as the Ganges and the Brahmaputra (Subramanian et al., 1987) in India, and the Mississippi in the USA (Tefry and Presley, 1976). They observed good correlations between major elements (Al-Si = -0.67; Al-Mg = 0.87; Na-K = 0.99) and between transition elements (Fe-V = 0.96; Fe-Ni =

0.93; Fe-Zn = 0.99; V-Zn = 0.95; Co-Ni = 0.94). They pointed to common sinks for elements showing good correlations.

Martin and Meybeck (1979) observed lower concentrations of Ca and Na, and higher concentrations of Al in suspended sediments of 15 major tropical rivers. Ramesh (1985) observed increase in Al corresponding to increase in clay minerals (Cited by Ramesh et al., 1989).

Martinelli et al. (1993) found 68.5% SiO_2, 15.2% Al_2O_3, 5.6% Fe_2O_3, 3.33% Na_2O, 2.54% CaO, 2.40% K_2O, 1.46% MgO and 1.00% TiO_2 in the Varzea sediment samples collected along the Amazon River floodplain. They observed losses of major elements such as Al, Fe, Ca, Mg and Na and enrichment of SiO_2 in the sediment as it traveled downriver and was deposited and eroded from the floodplain of the Amazon River. They attributed this observation to chemical and physical weathering of the sediment in its downward transport.

According to Manjunatha et al. (1996), chemical weathering predominates over physical weathering resulting in the enrichment of Al and Fe and depletion of Ca, Na, Mg, K, Rb, Sr and Ba in weathered products with respect to the average composition of surficial rocks.

Dupre et al. (1996) observed strong depletion of U, Rb, K, Ba, Sr, Na and Ca in the suspended sediments (Congo Basin) relative to the mean upper crust values (Taylor and McLennan, 1985) and an enrichment of the same elements in the dissolved phase. Viers et al. (2009) stated that Mg, Na and K were more strongly depleted in tropical environments than in temperate or boreal zones.

Canfield (1997) reported a significant positive correlation of Al, Fe and Mn concentrations (suspended sediments) versus runoff. According to Viers et al. (2009), higher proportion of soluble rock components leaches from the rock at higher runoff, concentrating Al, Fe and Mn in the particulate phase. Pokrovsky et al. (2005) reported that presence of ferromagnesian silicates or Fe-rich secondary phases in the drainage basin resulted in high Fe concentrations in suspended sediments. Viers et al. (2009) stated that high Mn concentrations might be encountered in both polluted and pristine rivers as Mn-enrichment might result from natural processes also [e.g. formation of authigenic particles in the fluvial environments (Ponter et al., 1992; Andersson et al., 1998)].

Singh and France-Lanord (2002) studied the chemical and isotopic compositions of sediments from the Brahmaputra River and its tributaries to trace sediment provenance and to understand erosion pattern in the basin. They concluded that erosion of the Himalayan rocks represented ca 70% of the detrital flux and the Siang-Tsangpo River were the major source of sediment to the whole Brahmaputra. According to them, erosion of the Namche Barwa represented about 45% of the total flux at its outflow before confluence with the Ganga. They also observed that sediments of the Brahmaputra, Ganga or other western Himalayan river contained lower Na and K values compared to average continental crust, which, according to them, showed that the sources were recycled crustal formations.

Mahanta and Subramanian (2004) reported the abundance and relative mobility of analysed elements in Brahmaputra bed sediments as Si> Al> Fe> Ca> Mg> Na> K> P> Mn> Zn> Cu> Cr> Pb> Cd and suspended sediments as Si> Al> Fe> Na> K> Ca> Mg> P> Mn> Zn> Cu> Cr> Pb> Cd. They observed enrichment of Fe (1.3×), K, P, Mn (1.4×), Zn (1.2×), Cu (1.6×), Cr (1.6×), Pb (1.8×), and Cd (1.3×) in suspended sediments over bed sediments in bulk phases. They found more Si in bed sediments than the world average and attributed its cause to the extensive physical weathering experienced by the basin comprising granite, gneiss and sandstone terrains under the influence of wet humid climate in the downstream region and transport of generated silicate minerals by the tributaries. Amongst the heavy metals, they found some correlation among Cu, Pb, Zn and Mn in the suspended sediments, but not in the bed sediments. According to them, metals in the sediments owe their origin more to natural than to anthropogenic sources. They stated that enormous amount of sediment load might have diluted the inputs from domestic, agricultural and industrial sources, which was also reflected by samples collected downstream of Guwahati, the biggest urban settlement along the river, showing no significant rise in elemental concentrations.

Viers et al. (2009) presented a new database on the chemical composition of suspended matter in World Rivers, together with the associated elemental fluxes. A part of the database is presented in Table 2.8.

Table 2.8: Average concentration of major and trace elements in the suspended sediments of world rivers (Viers et al., 2009) [σ = standard deviation; n = no. of samples]

Elements	Unit	Concentration	σ	n	upper crust	Martin and Meybeck	Savenko
Si	%	25.4	11.7	68	30.8	28.5	25.6
Al	%	8.72	6.01	140	8.04	9.4	8.63
Fe	%	5.81	4.81	144	3.5	4.8	5.03
Ca	%	2.59	2.8	118	3	2.15	2.6
K	%	1.69	1.04	119	2.8	2	2.15
Mg	%	1.26	1.4	93	1.33	1.18	1.44
Na	%	0.71	0.93	108	2.89	0.71	0.82
Mn	µg/g	1679	5011	148	600	1050	1150
Zn	µg/g	208	237	134	71	250	130
Cr	µg/g	130	155	149	35	100	85
Cu	µg/g	75.9	135	143	25	100	45
Ni	µg/g	74.5	100	164	20	90	50
Pb	µg/g	61.1	91.2	132	20	100	25
Cd	µg/g	1.55	4.15	70	0.098	-	0.5

The table also contains composition of the continental crust proposed by Taylor and McLennan (1985) as well as the chemical composition of riverine suspended sediments given by Martin and Meybeck (1979) and Savenko (2006), as reported by Viers et al. (2009).

2.4.2. Analyses of metals

Residual solid (the 5th fraction in sequential extraction) contain mainly primary and secondary minerals, which may hold trace metals within their crystal structures. These metals are not expected to be released in solution over a reasonable time span under the conditions normally encountered in nature (Tessier et al., 1979).

Tessier et al. (1979) reported higher concentration of trace metals in the residual fraction of sequential extraction procedure. He stated that the residual fractions of cobalt, nickel, zinc, iron and manganese accounted for more than 50% of the total metal concentration. Total metal analyses, therefore, are of less practical or environmental significance.

Grain size effects on heavy metal accumulation on sediments can be reduced by using relative atomic variation (RAV). Similarity in RAV implies a similarity or eventual homogeneity in a large number of processes in the geochemical cycle including weathering, transport, deposition, and biological perturbation. Only positive correlation, estimated using RAV method, with correlation coefficient greater than 0.4 should be considered as significant (Allan and Brunskill, 1976-cited by White and Tittlebaum, 1985).

Horowitz and Elrick (1987) found that trace element concentration in bed sediments (bulk) increased with increase in the proportion of <63 µm or <125 µm fractions. According to them, the <63 μm or <125 μm size fractions were more important to sediment-trace element levels and surface area than other finer fractions. They also observed that amorphous Fe oxides greatly influenced trace element concentration.

Subramanian et al. (1987) analyzed heavy metals in the bulk sediments of the Ganges and the Brahmaputra Rivers. Reported values for the Brahmaputra River are shown in Table 2.9. They observed excellent correlation between any two pairs of metals and, enrichment (3-6 times) of metals in suspended sediments over bed sediments. They attributed this enrichment to finer grain sizes and higher amounts of multiple-hydroxide coatings, organics, and trace metal scavenging clays in the suspended sediments.

Table 2.9: Concentrations (μg/g) of some metals in the sediments of the Brahmaputra River, Assam (Subramanian et al., 1987)

Elements	Bed sediments (n=21)	Suspended sediments (n=6)			
	(21 locations)	Dibrugarh	Guwahati	Dhubri	flux (10^{10} g/y)
Fe	24100-34400	80500	121900	125800	7778
Mn	542-721	2400	7250	3700	316
Cr	16-134	156	293	216	16
Ni	40-52	122	214	200	13
Zn	39-59	448	1500	800	65
Cu	13-22	59	207	58	8

Younger and Mitsch (1989) determined the concentrations of Ba, Cd, Cr, Cu, Fe, Pb, Mn, Ni and Zn in sediment samples of Ohio River. Concentrations of metals decreased with distance downstream, with highest values occurring in the industrial upper Ohio River. They observed reduction in concentrations of Cd, Cr, Cu, Fe, Pb, Ni and Zn in comparison to the values ten years ago. In contrast, Mn concentration was generally higher, while Ba levels did not differ. Most metal concentrations in the Ohio River remained greater by two to eight standard deviations than background concentrations of metals published for the State of Ohio.

Krumgalz (1989) observed a case of unusually high enrichment of anthropogenic trace metals and organic matter in the coarse and medium sand fractions (particles > 250 μm). They reported this to be due to formation of large agglomerations (clusters > 250 μm) from the smaller sediment particles (< 63 μm) enriched by contaminants (cited by Krumgalz et al., 1992).

In a study of the Ganga River sediments, Modak et al. (1992) observed that the order of release of metals was Cd > Cr > Pb > Cu > Zn > Ni > Mn > Fe, and the order of adsorption characteristics of most of the mobile metal fractions was Fe / Mn oxide > organic > clay.

Kabata-Pendias (1993) observed that minerals from the surface horizon of the soil were richer in Cu and Cr than were the same minerals from the parent rock, whereas Co, Ni and V were more concentrated in minerals from the parent rock than the top soil, reflecting higher mobility of Cu and Cr under weathering conditions. The author reported that concentration of Cu, Co, Zn, Ni and Pb fixed by Fe-Mn oxides were much higher than that by organic matter. He also observed that easily mobile metals (Zn and Cd) existed mainly as organically bound, exchangeable, and water soluble species, while slightly mobile metals (Pb, Ni and Cr) were mainly bound in silicates (residual fraction).

Sabri et al. (1993) observed higher concentrations of Cd, Cu, Co, Zn, Pb, and Ni in suspended sediments compared to bed sediments of the Tigris River. They observed higher concentration of Fe in the sediments and stated that to be the reflection of the character of the soil in the region. They ascribed the high positive inter-metal correlations to the compositions of the rocks and soils in the catchments, and the negative correlations of Mn with other metals to the competitions between cations in the sediments (Cited from Wood, 1987). They observed significant negative correlations of Zn, Pb and Ni with suspended sediment load. They stated that such results need further investigation on the particle size- metal concentration relationships.

Subramanian (1993) studied the mineralogy, particle size and concentrations of Fe, Mn, Cu, Pb and Zn in the sediments samples collected from Ganges estuary during monsoon (July), early winter (November) and late winter (February). He has observed enrichment of coarse quartz grains in the sediments. He has also found that metal concentrations in suspended particulate materials are more than that in the bed sediments. The mean values of various metals are shown in Table 2.10.

Table 2.10: Concentrations of some metals in the Ganges estuary sediments (Subramanian et al., 1993)

Metals	Concentration in suspended sediments (µg/g)		Concentration in bed sediments (µg/g)
	Monsoon	Winter	winter
Mn	630	730	550
Cu	45	44	26
Pb	43	32	29
Zn	115	150	71

Speciation studies of metals for the Yamuna River sediments revealed Cd association with carbonate, Cu with organic matter and Zn/Pb with Fe-Mn oxides (Gadh et al., 1993).They observed relatively high percentages of aluminium and attributed it to immense weathering processes which removed most of the elements to concentrate aluminium in the sediments (cited from Ramesh, 1983).

Wang and Chen (2000) studied the sediment characteristics (grain size distribution, iron, manganese and their oxyhydroxides, aluminum, total organic carbon, surface area and surface site density) and Cd, Cu, Pb and Zn concentrations of some major rivers of China. They observed that correlation between trace metal concentrations and the sediment characteristics were actually due to interrelation among the sediment characteristics themselves. According to them, trace metal concentrations of the relatively uncontaminated sediments can be better interpreted by the sediment surface area and aluminum content. But under elevated aqueous metal concentrations, Cd, Cu, Pb and Zn sorption on the sediments were contributed mainly by FeOOH, MnOOH and TOC, instead of by aluminum (Wang et al., 1997).

Surface of clay minerals in natural sediments may be masked by sorbed FeOOH, MnOOH and organic matter (Jenne, 1968) and their surface will have little access to sorb trace metals. Tessier et al. (1996) found that, depending on pH, organic matter sorbed on the surfaces of FeOOH or MnOOH may or may not mask the reactivity of the underlying oxides. Thus, the laboratory observed adsorptive additivity (the total amount of the sorbed metal simply equals the addition of the amounts sorbed to discrete sorbents) (Honeyman and Santschi, 1988) is unlikely to be true in natural sediments.

Yu et al. (2001) reported that competitions of various sediment phases (carbonates, Mn-oxides, organic matter and Fe-oxides) occurred for binding with heavy metals, and organic matter and Fe-oxides were more accessible to heavy metals than other sediment matrices.

Binning and Baird (2001) analyzed sediments of the Swartkops River and its estuary and observed considerable increase in metal concentrations (Pb = 270%; Mn = 189.6%; Sr = 126.4%; Cr = 116.2%; Zn = 95.9%; Cu = 72.1%) compared to a similar study conducted by Watling and Watling (1979). Continuous increase of metals in the estuary may lead to their bioaccumulation in the tissues of biota affecting distribution and density of benthic organisms, and composition and diversity of infaunal communities (Gyedu-Ababio et al., 1999).

van Aardt and Erdman (2004) observed higher Pb concentrations in fish tissues in that section of the Mooi River (South Africa) where Pb concentrations were higher in the sediments.

Tsai et al. (2003) observed strong positive correlations (r = 0.83-0.95) between extractable heavy metals (Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn) and organic matters (concentration range between 0.6 to 3.8%) in sediments of the Yenshui River, Taiwan. They found that the slopes of the linear regressive lines approximated the average metal complexation ratios with organic matters in the sediments. They reported that the complexation ratios for moderately polluted river sediments were smaller than those for highly contaminated river sediments, indicating the importance of organic matters in the accumulation of heavy metals in river sediments.

Lin et al. (2003) investigated the distribution of metal speciation in different particle-size fractions of sediments from two rivers (the Ke-Ya and the Ell-Ren Rivers) in Taiwan. They found accumulation of heavy metals in the silt/clay fractions (<25 µm) and coarse sands (420-2000 µm) as well. Presence of high concentration of organic matters was attributed to the accumulation of heavy metals in the coarse fraction. Surija and Brancia (1995) found that organic matter had higher specific surface areas (1900 m^2/g) than Fe/Mn oxides (300 m^2/g) or carbonates (<1 m^2/g). Potential toxicity to the aquatic ecosystem caused by the coarse sediments should be considered along with that by the fine sediments (Lin et al., 2003).

Ackay et al. (2003) studied environmental pollution levels for trace elements in Gediz and Buyak Menderes rivers, Turkey. They reported that the high concentrations of Zn, Mn and Cr might result from industry and pesticides used in agriculture, and Fe concentrations from Fe-rich metamorphic rocks in the river basins.

Jana (2005) observed high positive correlations between metal concentrations with coarse silt or fine sand, and high negative correlations with clay, fine silt or medium silt in the Brahmaputra sediments. Correlation coefficients (r) as reported by him are reproduced in Table 2.11.

Table 2.11: Correlation coefficients of the relationship between concentration of metals and concentration of various fractions of sediment of the Brahmaputra River, Assam (Jana, 2005)

	Cu	Pb	Mn	Cr
Clay	-0.91	-0.83	-0.99	-0.97
Fine silt	-0.95	-0.92	-0.99	-0.999
Medium silt	-0.96	-0.95	-0.99	-0.996
Coarse silt	0.93	0.91	0.99	0.98
Fine sand	0.97	0.97	0.97	0.99

He concluded that adsorption played insignificant role in controlling metal concentrations in the Brahmaputra sediments, and the observed values might be contributed solely by the residual fractions (embedded in crystal lattices) of the sediments. It is worth mentioning that his conclusion was based on analyses of only five samples.

Borah (2006) observed a downstream increase in metal concentrations in the Brahmaputra River sediments. She attributed this to downstream reduction in grain sizes of the sediments in the river. In her results, concentrations of Fe, Mn and Pb were higher in post-monsoon; concentrations of Cu, Na and Si were higher in pre-monsoon and no such trend for the rest (Zn, Cr, Mg, K, Ca and Al) of the elements. Overall concentration values (μg/g) of the elements were as follows: Si = 245743 ± 50394, Al = 27868 ± 13783, Fe = 28372 ± 8146, K = 4453 ± 364, Ca = 8706 ± 594, Na = 547 ± 117, Mg = 1506 ± 557, Mn = 2411 ± 853, Cr = 177 ± 49, Cu = 16.8 ± 2.4, Pb = 15.3 ± 2.8, Zn = 55.8 ± 11.6. Analysis of her results revealed enrichment of Si and Fe and depletion of Al, K, Ca, Na, and Mg in the sediments compared to upper crust values (Taylor and McLennan, 1985). Concentrations of Cr and Mn were higher, and Cu, Pb and Zn were lower than the average concentration of these elements in World Rivers (Viers et al., 2009).

Saxena (2006) analyzed Brahmaputra sediments for some metals. He found concentrations (μg/g) of metals as follows: Al = 66830.77 ± 1088.87, Fe = 66638.46 ± 11215.28, Mn = 904.62 ± 70.49, Cr = 83.00 ± 17.70, Cu = 54.69 ± 9.76, Pb = 26.08 ± 4.25, Zn = 111.92 ± 10.59, Ni = 67.69 ± 10.73 and Cd = 256.92 ± 124.79. Concentration of Cd in his results is abnormally higher than the average Earth Crust value (1.55 μg/g) (Taylor and McLenna, 1985), which might result from some systematic errors in his analyses. Except for Cr and Mn, other values reported by him are more than twice of that reported by Borah (2006). This comparison is based on samples collected from approximately the same location of the river. The variability in the values obtained by different authors in the same sampling location points to the complexities involved in generating data for river sediments (Biksham and Subramanian, 1988). Saxena (2006) conjectured the possibility of the presence of discrete metal ions to justify high concentrations of some metals (e.g. Fe, Al) in his results for the Brahmaputra sediments.

2.5. Summary of literature review

The Himalayas, where the Brahmaputra River originates, are among the youngest and most active mountain ranges on the planet, with high relief, steep gradients, frequent tectonic activity, intense monsoon rainfall, and highly erodable rocks (Clift et al., 2008). Sediment yield of a basin is generally controlled by climate (precipitation, temperature), lithology, land use, earthquake and physiographic characteristics (basin area, relief, vegetation, soil erodibility) (Janssen and Painter, 1974; Dunne, 1979; Goswami, 1985; Ludwig and Probst, 1998; Vanacker et al., 2007). These explain the high sediment yielding nature of the Brahmaputra basin. Moreover, resuspension of bed sediments and bank scour during high flows also contribute significantly to the suspended sediment load (Datta et al., 1999). Few estimates of sediment load transported by the river are available near the sampling site of the present study (e.g., 675 million tons/year by Subramanian, 1979; 402 million tons/year by Goswami, 1985).

Suspended sediments of the Brahmaputra River are silt with clay fractions (< 2 µm) representing 0.5-3% of the total sediment load (Singh and France-Lanord, 2002). The surface sediment load consists of 12.5% coarse, 14.2% medium and 73.3% fine fractions (Datta and Singh, 2004). Median diameter of the bank and bed sediments varies from 0.08 mm to 0.22 mm of which finer size belongs to the bed sediments (WAPCOS, 1993).

Brahmaputra sediments are dominated by quartz and feldspars (e.g., Singh and France-Lanord, 2002; Mahanta and Subramanian, 2004), and illite is the major clay mineral (e.g., Heroy et al., 2003; Mahanta and Subramanian, 2004). Brahmaputra sediments contain montmorillonite also (Mahanta and Subramanian, 2004), although some other reports inform its absence (Subramanian, 1980; Sarin et al., 1989; Datta and Subramanian, 1997). Epidote to Garnet ratio is more than 1 in the sand fractions of the Brahmaputra sediments, which is a diagnostic feature to identify source of sediments in the Bengal basin (Heroy et al., 2003).

Abundance of elements in Brahmaputra sediments are as follows: bed sediments- Si> Al> Fe> Ca> Mg> Na> K> P> Mn> Zn> Cu> Cr> Pb> Cd; suspended sediments- Si> Al> Fe> Na> K> Ca> Mg> P> Mn> Zn> Cu> Cr> Pb> Cd (Mahanta and Subramanian, 2004). Enrichment of Fe and Si, and depletion of Ca and Na with respect to world surface rocks were observed for Brahmaputra suspended sediments (Bora, 2004) indicating predominance of chemical weathering (Manjunatha et al., 1996). Suspended sediments are usually enriched in most of the elements in comparison to bed sediment composition (Subramanian et al., 1987; Ramesh et al., 1989; Mahanta and Subramanian, 2004).

Excellent correlation is observed between different pairs of metals in the Brahmaputra sediments (e.g., Subramanian et al., 1987). Metals in the sediments of the Brahmaputra River are mostly contributed by natural sources and their unchanged concentrations even in the downstream of Guwahati (the biggest urban settlement along the river) suggest dilution by enormous amount of sediment in the river (Mahanta and Subramanian, 2004).

CHAPTER 3

MATERIALS AND METHODS

3. Introduction

Water samples (from a depth of about 1 m from the water surface) were collected from the Brahmaputra River for analyzing concentration, particle size, mineralogy, chemical composition and metal-contents in the suspended solids. The fraction of sediments extracted from the aforementioned water samples will be referred to here onwards as 'Top Water Layer Suspended Sediment' (TWLSS) here.

Continuous daily data of discharge (from 15th May 2001 to 15th October 2008) and suspended sediment (from 1st December 2003 to 15th October 2008) were obtained from Central Water Commission (CWC), Middle Brahmaputra Division, Government of India. CWC collects depth-integrated water samples along a cross section of the river at about 100 m downstream of the sampling site of the present study with the help of a vessel on the open water. Suspended solids data of CWC were generated using these water samples. CWC data could be used for comparison or in combination with the data generated in the present study due to proximity of sampling locations.

3.1. Collection and storage of samples

Sampling was started from October 2004 and was continued up to April 2007. The sampling points were located along a cross-section (Wren et al., 2000) of the river parallel to and downstream of the Saraighat Bridge on the Brahmaputra River on the downstream side. The width of the river at this section is about 1.3 km. The sampling points were equally spaced at about 246 m interval, the extreme ones being away from the banks by about 154 m. Due to unavailability of samplers, samples were collected from the bridge with a rope and a plastic bucket (Sarin and Krishnaswami, 1984; Datta and Subramanian, 1997; Singh et al., 2005). Moreover, as the river remains mostly inaccessible at its high flows and plying of boats are also prohibited during that time, sampling from the bridge ensured continuous and consistent sampling. During each sampling, five grab samples of surface water of 10 L volume were collected from the aforementioned sampling points following same approach to ensure inter-sample comparability. All efforts were made to carry out the sample collection in such a manner that the suspended load in the sampling regime is represented as authentically as possible, considering their proximity to the piers, and recognizing that this was the only feasible option possible. Approximate sampling locations (S1, S2, S3, S4 and S5) are shown in the Figures 3.1 and 3.2. The samples were collected in plastic containers and were transported in ice box to the laboratory. A table showing dates of sampling and number of samples collected has been furnished in Appendix-IV.

After reaching the laboratory, 100 mL of well mixed composite water sample from each container was filtered through 0.45 µm membrane filter for determination of suspended solids concentration. The filtrate was acidified to a $pH < 2$ (for stabilization of various cations) and then stored in refrigerator for determination of dissolved metals in the water (Khanna et al., 2009). The remaining sample was kept undisturbed for a week at a temperature below 4 ºC (Datta and Subramanian, 1997). About 9 L of water was then siphoned off from each of the containers without disturbing the settled sediments, thereby concentrating the samples in sediments. This was necessary due to low suspended sediment concentrations in the collected water samples, which was insufficient to produce required obscuration for particle size analysis by Malvern Particle Analyzer. The remaining sample was filtered through 0.45 µm membrane filter and the suspended sediment retained was dried in the oven at 70-80 ºC (Sabri et al., 1993) for 24 hours. The dried sediment was collected and stored in plastic containers for further analyses.

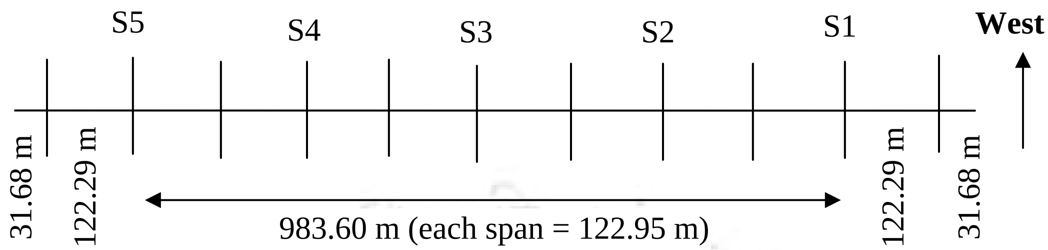


Figure 3.1: Schematic drawing of the spans of the (Brahmaputra) Saraighat Bridge and the approximate locations of the sampling points (Source: Signpost at bridge entrance)

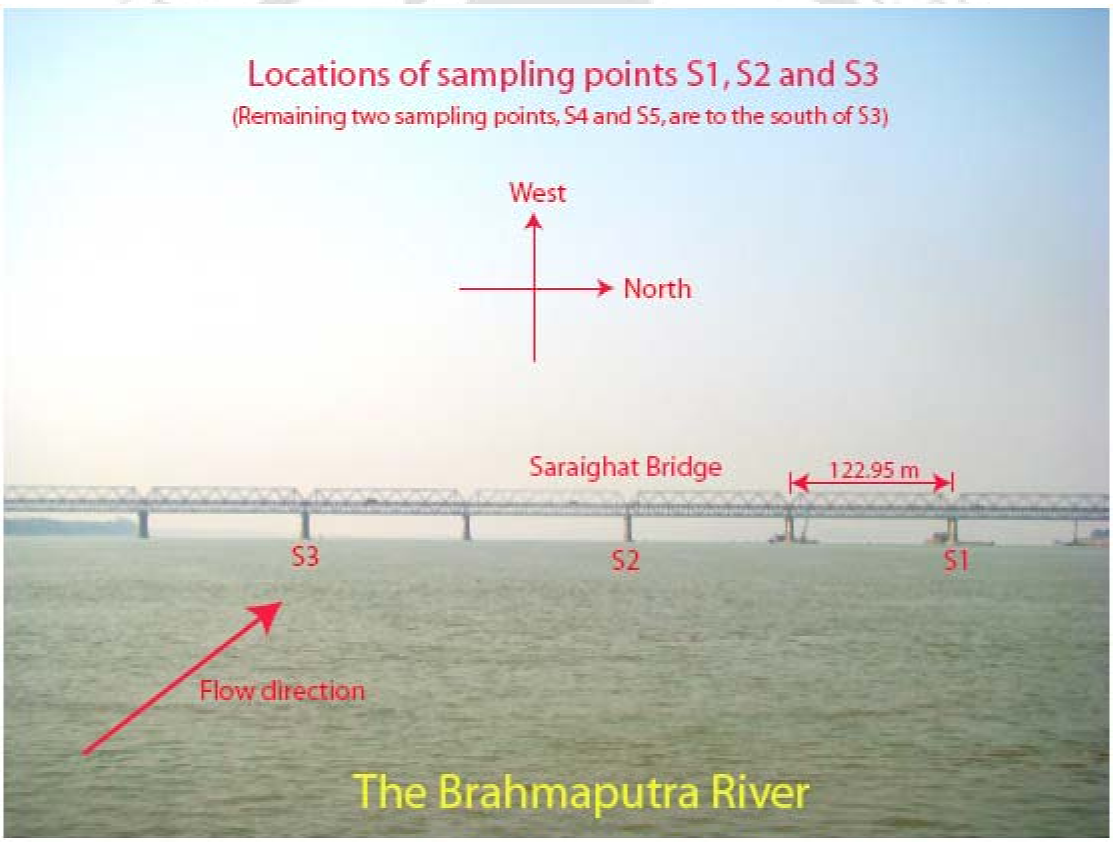


Figure 3.2: Some sampling locations (photo taken from a distance of ~2 km)

Bed sediments samples (Figure 3.3) of about 300 g were collected by scooping up sediments with a plastic spade from the upper 3-5 cm of the river bed at a water depth of 50-100 cm (Datta and Subramanian, 1998), taking care not to lose the fine [All possible care was taken. Collecting the sample by two scoops in a face to face position and lifting them as slowly as possible, protecting these from wind]. Only polyethylene scoops and cans were used for sampling and storage. The samples were put in ice bags during transportation to the laboratory and stored in deep freeze unit until drying them.

Figure 3.3: Bed sediment sampling location (Not to scale)
(Source: www.google.com, as on 28-08-2011)

The samples were oven-dried at 70-80 °C (Sabri et al., 1993), cooled in desiccators and stored in plastic containers for further analyses.

All chemicals used in this study were of analytical grade. Deionised water was used in particle size and metal analyses. All glassware and other containers were thoroughly cleaned by soaking in detergent followed by soaking in 10% HNO_3 for 48 hours and finally rinsed with deionised water several times prior to use (Jain and Ram, 1997).

3.2. Analyses

3.2.1. Suspended sediment concentration

Suspended solids concentration in the top water layer of the Brahmaputra River was calculated by simple unitary method. As the samples collected in the present study was not depth-integrated ones, total suspended sediment transported by the river through the sampling site was calculated using CWC data. Monthly or annual sediment load was calculated by summing the product of daily concentration and daily discharge during the specified month or the year (Quilbe et al., 2006).

3.2.2. Particle Size Analysis

Several soil physical properties depend upon particle size distribution of soils. In fact, particle size distribution (PSD) is the basic determinant of almost all the physical phenomena. Efforts to employ this vital parameter to characterize a number of physical properties have gained momentum during the recent years.

3.2.2.1. Description of the instrument used and principle of analysis

Malvern Particle Analyser (Mastersizer 2000) (Figure 3.3) was used for the Particle Size Analysis (PSA). The standard result range for the Mastersizer 2000 is 0.02 to 2000 microns. It is capable of analyzing emulsions, suspensions or dry powders. The basic result produced by the analysis is a volume distribution which is the volume proportion within each size class of the total volume of the particles. The result can be edited at a later date by changing any of the parameters (e.g., refractive index) used during the measurement. The analysis is carried out with a combination of an accessory (e.g., Hydro 2000G), an optical unit and a stand-alone computer that runs the Malvern Software. The software controls the optical unit and the accessory and also analyses the raw data from the optical unit to give the size of the particles. Hydro 2000 MU (A), a sample dispersion accessory, is controlled from the key pad, not from the software.

The Malvern Particle Analyser works on the principles of Mie Theory. Mie theory was developed to predict the way light is scattered by spherical particles and deals with the way light passes through, or is adsorbed by, the particle.

Knowledge of refractive index of the particle and its absorption is necessary for using this theory. When no published information is available, determining the most appropriate choice of refractive index is achieved by a process of looking at the fit and residual and selecting the refractive index that minimizes these values.

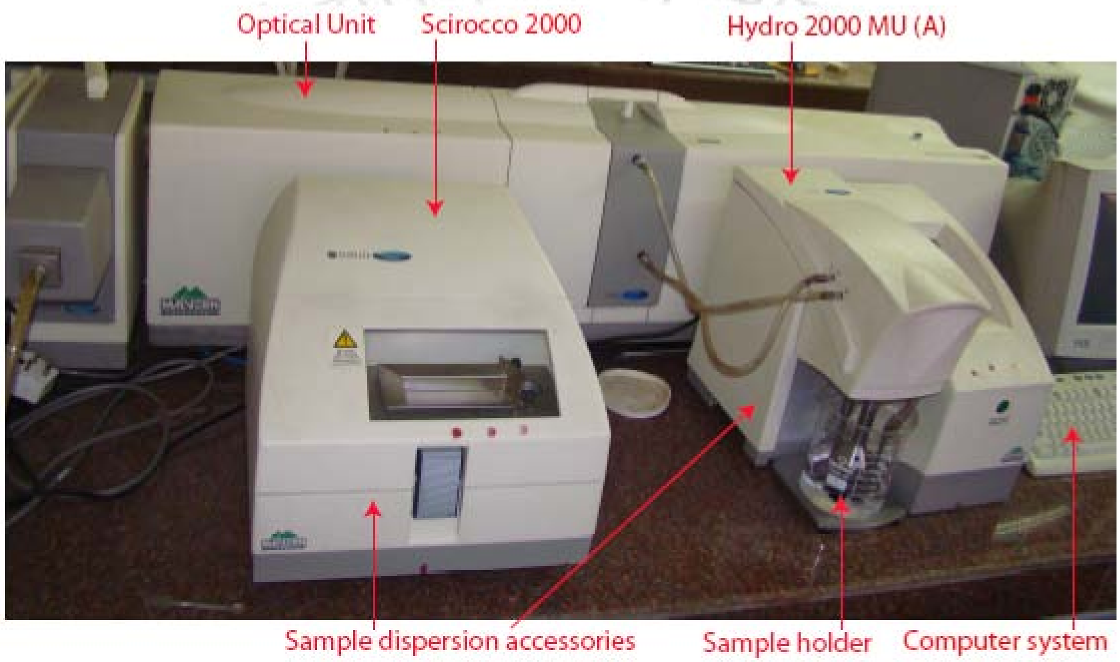


Figure 3.4: The Malvern Mastersizer 2000 used in Particle Size Analyses [Civil Engineering Department Laboratory, IIT Guwahati]

Size and other details about the structure of the particle dictate the way it will scatter light. Each size of particle will have its own characteristic scattering pattern, like a fingerprint, that is unlike any other size of particle. The Mastersizer uses the optical unit to capture the actual scattering pattern from a field of particles and calculate the size of the particles that created the pattern by using the Mie theory.

There are three distinct procedures involved in measuring a sample on the Mastersizer:

- The sample is prepared and dispersed to the correct concentration and then delivered to the optical unit for measurement. This is done by the sample dispersion accessory. Values of pump speed and ultrasonic power is incorporated in the Standard Operating Procedure (SOP).
- The optical unit captures the scattering pattern from the prepared sample. The detector array within the optical unit is made up of many individual detectors. Each detector will collect the light scattering from a particular range of angles. The detector array takes a "snap-shot" of the scattering pattern. For getting a representative reading of the scattering pattern, the Mastersizer makes over 2000 snaps for each measurement and averages the result. Each snap takes 1 millisecond. The detectors and windows should be kept clean at all times for correct results.
- When the measurement is complete, the raw data contained in the measurement are analyzed by the Malvern software.

Sample should be added one drop at a time. Care must be taken to ensure that the sample is thoroughly mixed. Bubbles interfere with the measurement. When the dispersant has been added to the accessory and circulated, it is advisable to switch off the unit for a brief period to allow trapped air to rise out of the system. There should be no twists or loops in the connected sample tubing. The pump and stirrer speed should not be so fast which can introduce air into the system.

Obscuration bar should be in the green region. The obscuration is simply the fraction of light "lost" from the analyzer beam when the sample is introduced. If the obscuration bar is in the green zone then the concentration is in the correct range. A mid value in the green region is recommended. If it is in the red then the concentration is out of range. The instrument has wide range of concentrations that are acceptable and thus concentration do not have to be precise. A measurement should not be made until the obscuration has stabilized-indicating that the sample has properly dispersed. In general, enough sample should be added to give the following obscurations:

- 10% obscuration for very fine (up to 3-4 µm) materials
- 15% obscuration if the median size of the material is 50 µm or greater
- 25% obscuration if the material has a broad distribution or is coarse

The measurement data from a particle field is contaminated by background electrical noise and also by scattering data from dust on the optics and contaminants floating in the "clean" dispersant. The "Measure background" facility makes a measurement of the system with only clean dispersant in as well as a measurement of the electrical background. This background information is subtracted from the sample measurement in order to "clean" the data.

3.2.2.2. Sample analysis

In the present study, Hydro 2000 MU (A) was the accessory used as dispersion unit for the particle size analysis. A beaker was used for holding the sample for dispersion and subsequent delivery to the optical unit. About 600 mL (for proper immersion of the stirrer) of deionised water (dispersant) was first placed in the beaker for measurement of background values. River water sample concentrated in suspended sediment was added to the beaker drop by drop after "Add sample" message appeared on the computer window. Sufficient amount of sample was added to bring the obscuration bar to the middle of the green region (about 15% obscuration). The pump speed used was

2500 rpm. No agglomeration of sediment was seen in the dispersed sample and so ultrasonic was not used in the analysis. The accessory and the sample holder (a beaker) were flushed between measurements (by drain button) to avoid cross-contamination of samples.

3.2.2.3. Report of the results

Particle size properties such as uniformity, specific surface area, surface weighted mean D[3,2], volume weighted mean D[4,3], d_{10}, d_{50} and d_{90} are furnished in result analysis report in addition to the size distribution curve.

3.2.3. Morphological and major element analysis

Morphological study of the sediment was done by Scanning Electron Microscope (SEM). SEM provides high resolution and 3-D like images of solid samples. Variations in the surface topography of a material are depicted as variations in gray level of the image. Details as small as 70 Å can be resolved on most samples. Compositional details were obtained with EDS (energy dispersive X-ray Spectroscopy) equipment fitted with the SEM.

SEM uses electrons rather than light to form image. The combination of higher magnification, larger depth of focus, greater resolution, and ease of sample observation makes the SEM one of the most heavily used instruments in research areas today [http://epmalab.uoregon.edu/UCB_SEM/#intro].

3.2.3.1. Description of the instrument used and principle of analysis

Morphology and structure investigations were performed using LEO 1430 VP SEM (Figure 3.4) with 10, 15 and 20 kV accelerating voltages. Elemental analysis of the sediments was performed by EDS on the same LEO 1430 VP.

In the SEM a finely focused electron beam (Figure 3.5) interacts with the sample to induce the emission of X-rays (EDX) in the samples that are characteristic of the elements present. EDS extends the usefulness of SEM in that elemental analysis can be performed within regions as small as a few cubic micrometers. All elements from boron through the periodic table can be detected with sensitivities of approximately a few tenths of one percent. EDS Spectra is a graphical plot of peaks identifying elements detected within the area analyzed. The area analyzed can be adjusted to encompass sub micrometer or several millimeters. The intensity of peaks (peak height) is related to the elemental concentration (http://www.microanalytical.com /sem.html).

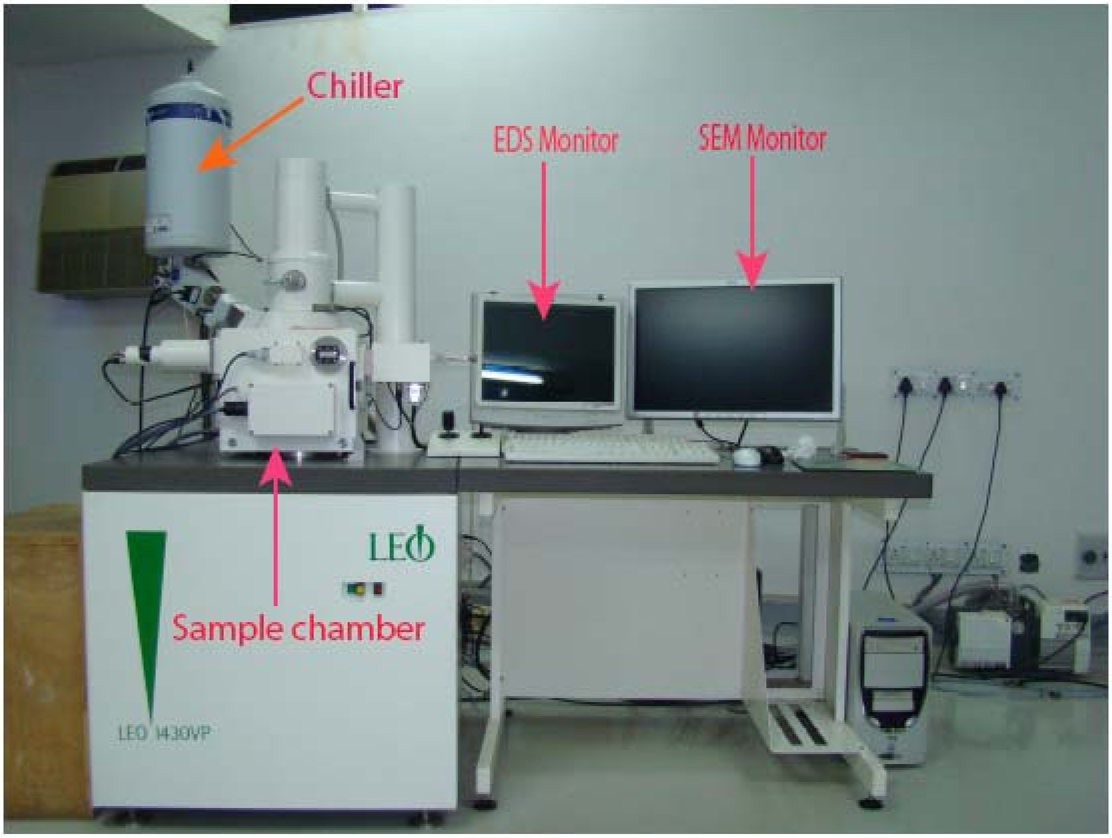


Figure 3.5: The SEM used for analyses of morphology and composition of sediment samples [Central Instrument Facility, IIT Guwahati]

Energy dispersive x-ray spectroscopy (EDS) is a chemical microanalysis technique performed in conjunction with a scanning electron microscope. The technique utilizes x-rays that are emitted from the sample during bombardment by the electron beam to characterize the elemental composition of the analyzed volume. When the sample is bombarded by the electron beam of the microscope, electrons are ejected from the atoms comprising the sample's surface. A resulting electron vacancy is filled by an electron from a higher shell, and an x-ray is emitted to balance the energy difference between the two electrons. The EDS x-ray measures the number of emitted x-rays versus their energy. The energy of the x-ray is characteristic of the element from which the x-ray was emitted. A spectrum of the energy versus relative counts of the detected x-rays is obtained and evaluated for qualitative and quantitative determination of the elements present in the sampled volume.

Electron microscopy has been used for the study of soils and sediments since the 1940's (Jackson et al., 1946), although early uses were limited to the description of particles in terms of shape, size and reaction to certain chemicals (de Boer and Crosby, 1995).

3.2.3.2. Sample preparation and analysis

In order to be observed with a SEM, objects need first to be made conductive for current. This is done by coating them with an extremely thin layer (1.5 - 3.0 nm) of gold or gold-palladium. Furthermore, objects must be able to sustain the high vacuum and should not alter the vacuum, for example by losing water molecules or gases [http://www.vcbio.science.ru.nl/en/fesem/info/preparatie/].

Samples were mounted on aluminum stubs for gold-coating and analysis by the

SEM. Adhesive tapes on the stubs, if any, were removed with a knife and the surfaces of the stubs were cleaned with tissue paper dipped in 2-propanol and covered with a conductive carbon double-sided tape. Powders agglomerate, are hard to distribute evenly

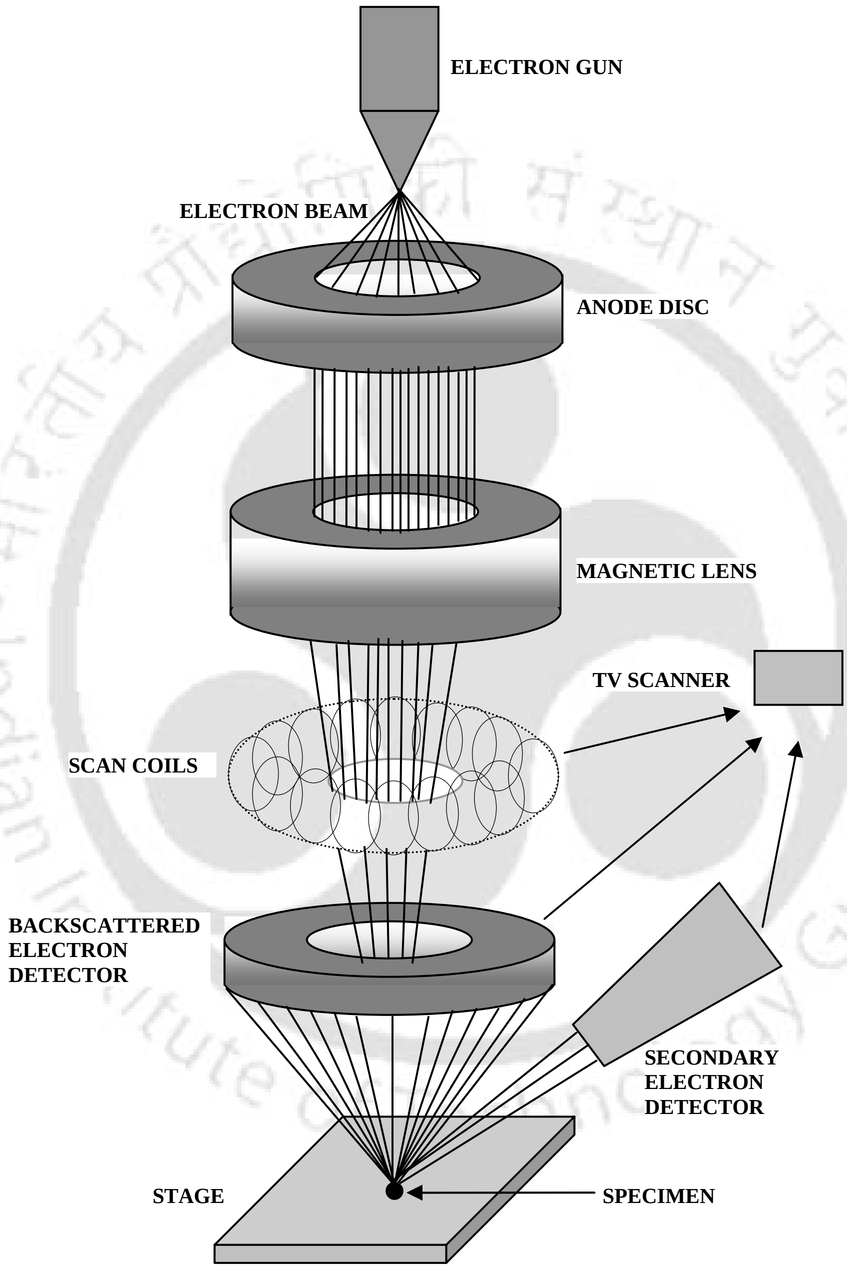


Figure 3.6: Schematic view of the components of a scanning electron microscope (Source: www.purdue.edu/REM/rs/graphics/sem2.gif)

on a surface, and can easily fly off the stub in the vacuum in the SEM chamber making their analyses difficult. For better results, the sample should be thinly spread on the stub. When this was done, the stubs were placed inside the Sputter Coater (Polaron Range SC 7620, Quorum Technology, Newhaven, England) (Figure 3.6) and the processes for coating the samples were started. After completion of the coating operation, the stubs were placed inside the SEM chamber and morphological and compositional analyses were performed with the help of the software loaded in the computers connected to the SEM.

3.2.3.3. Report of the results

The results of SEM-EDS analyses consist of micrographs of the sediment particles, spectrums showing major elements contained in the sample and tables of weight % and atom % of the major elements. The SEM micrographs provide a quick estimate of the particle sizes of the sediments.

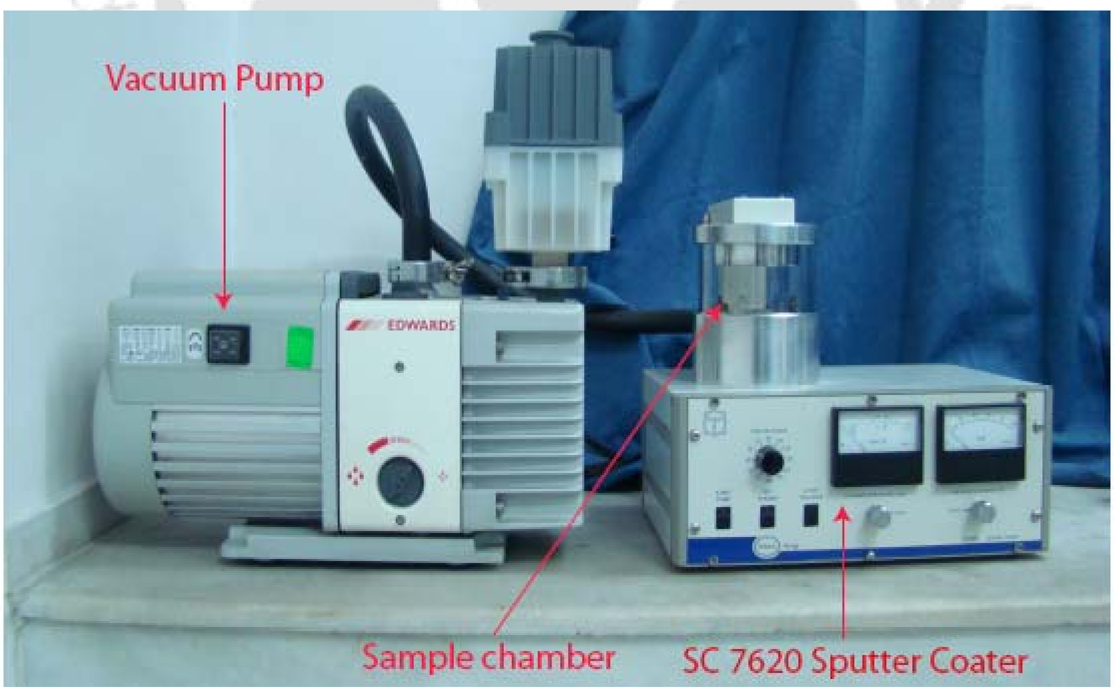


Figure 3.7: The Sputter Coater used for gold-coating of sediment samples [Central Instrument Facility, IIT Guwahati)

3.2.4. Mineralogical analysis

3.2.4.1. Principles involved in X-Ray Diffraction

Diffraction is the interference between waves that occurs as a result of an object in their path. X-Rays are scattered by the electrons in atoms (Figure 3.7) and diffraction

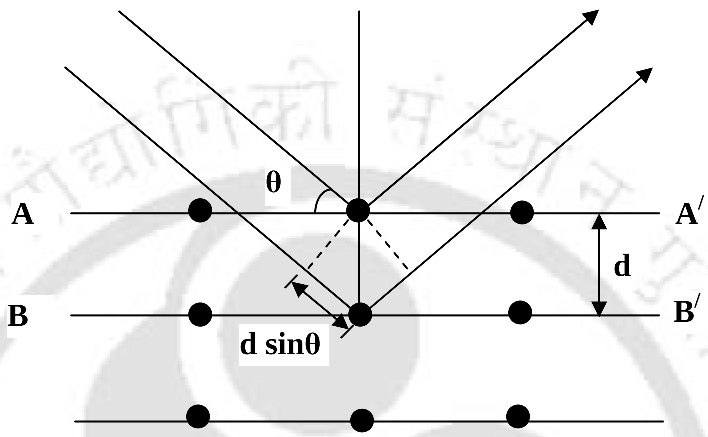


Figure 3.8: Diffraction of x-rays by planes of atoms (A-A/ and B-B/) (Levine, 2007)

occur for a periodic array of scattering centres separated by distances similar to the wavelength of the radiation (about 100 pm), such as a crystal. If we think of scattering as equivalent to reflection from two adjacent parallel planes separated by a distance d (Figure 3.7) then the angle at which constructive interference occurs between waves of wavelength λ is given by the Bragg equation:

$$2d \sin \theta = \lambda$$

The two theta values for some individual minerals are shown in Table 3.1. The intensity of diffraction depends on the details of the crystal structure and the identities of the atoms. How well an atom scatters X-Rays is related to how many electrons it possesses and its location in the unit cell. Thus measurement of diffraction angles and intensities allows us to work backwards to structural information.

Table 3.1: Minerals and their 2θ values

(A)

Primary Minerals	
Name	**2θ (degree)**
Quartz	26.6
Feldspar	27.5
Calcite	29.6
Dolomite	31
Siderite	31.8
Pyrite	33.1
Clays	19.9
	34.6
	61.9

(B)

Secondary Minerals	
Name	**2θ (degree)**
Smectite	5.1
Illite	8.9
Chlorite	9.1
Gypsum	11.7
Kaolinite	12.5
Barite	28.9
Halite	31.7

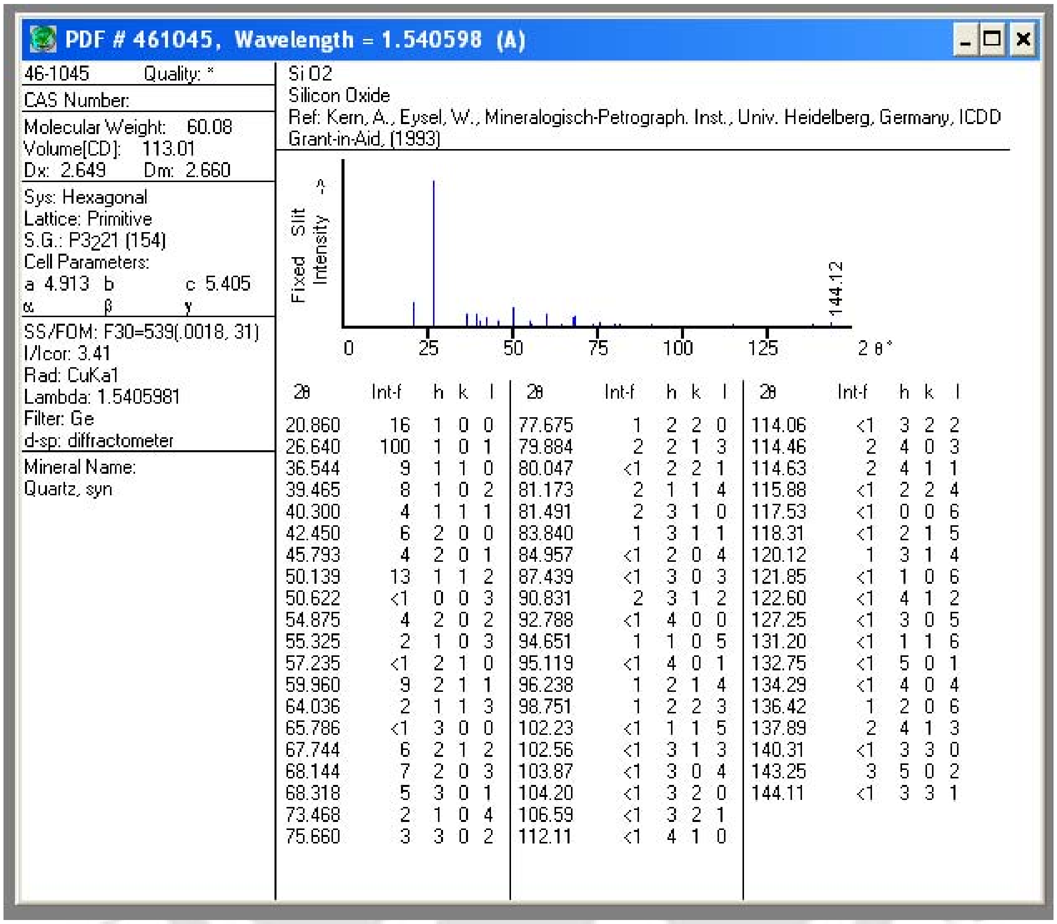
There are two principal X-Ray techniques: the **powder method**, in which the materials being studied are in polycrystalline form, consisting of thousands of crystallites of a few micrometers or less in dimension, and **single crystal diffraction**, where the compound is available as a single crystal of dimensions of several tens of micrometers or larger.

A powder sample contains an enormous number of very small crystallites, typically 0.1 to 10 μm in dimension and oriented at random. An X-Ray beam striking a polycrystalline sample is scattered in all possible directions. As a result, each plane of atoms separated by different lattice spacing in the crystal gives rise to a cone of diffraction intensity. Each cone consists of a set of closely spaced dots, each one of which represents diffraction from a single crystallite within the powder sample. With a very large number of crystallites these dots join together to form the diffraction cone. To obtain powder X-Ray diffraction data in a form of useful analysis, the positions of the various diffraction cones need to be determined. This can be achieved by using either photographic film or a detector sensitive to X-Ray radiation. In each case the basic idea is to determine the diffraction angle, θ, of the various diffraction cones. A powder diffractometer uses an X-Ray detector to measure the positions of the diffracted beams. Scanning the detector around the sample along the circumference of a circle cuts through the diffraction cones at various diffraction maxima and the intensity of the X-Rays detected is recorded as a function of the detector angle.

The number and positions of the diffraction maxima, which are normally referred to as reflections, depend on the cell parameters, crystal system, lattice type, and wavelength used to collect the data; the peak intensities depend on the types of atoms present and their positions. Nearly all crystalline solids have a unique powder X-Ray diffraction pattern in terms of their positions of the observed reflections and their intensities. In mixtures of compounds, each crystalline phase present contributes to the powder diffraction pattern its own unique set of lines and the relative intensities of line sets from mixtures depend on the amount present and the ability of a structure to scatter X-Rays.

The effectiveness of powder X-Ray diffraction has led to it becoming the major technique for the characterization of polycrystalline, solid inorganic materials. Many of the powder diffraction data sets collected from inorganic, organometallic, and organic compounds have been compiled into a database by the Joint Committee on Powder Diffraction Standards (JCPDS) (e.g., Figure 3.8, a powder diffraction file for quartz). This database, which contains over 50,000 unique powder diffraction patterns, can be used like a fingerprint library to identify an unknown material from its powder pattern alone.

The presence or absence of certain reflections in the diffraction pattern permits the determination of the lattice type. In recent years the technique of fitting the intensities of the peaks in the diffraction pattern has become a popular method of extracting structural information such as atomic positions (Rietveld Method) (Atkins et al., 2006).



PDF # 461045, Wavelength = 1.540598 (A)

46-1045 Quality: *
CAS Number:
Molecular Weight: 60.08
Volume[CD]: 113.01
Dx: 2.649 Dm: 2.660
Sys: Hexagonal
Lattice: Primitive
S.G.: P3221 (154)
Cell Parameters:
a 4.913 b c 5.405
α β γ
SS/FOM: F30=539(.0018, 31)
I/Icor: 3.41
Rad: CuKa1
Lambda: 1.5405981
Filter: Ge
d-sp: diffractometer
Mineral Name:
Quartz, syn

Si O2
Silicon Oxide
Ref: Kern, A., Eysel, W., Mineralogisch-Petrograph. Inst., Univ. Heidelberg, Germany, ICDD Grant-in-Aid, (1993)

2θ	Int-f	h	k	l	2θ	Int-f	h	k	l	2θ	Int-f	h	k	l
20.860	16	1	0	0	77.675	1	2	2	0	114.06	<1	3	2	2
26.640	100	1	0	1	79.884	2	2	1	3	114.46	2	4	0	3
36.544	9	1	1	0	80.047	<1	2	2	1	114.63	2	4	1	1
39.465	8	1	0	2	81.173	2	1	1	4	115.88	<1	2	2	4
40.300	4	1	1	1	81.491	2	3	1	0	117.53	<1	0	0	6
42.450	6	2	0	0	83.840	1	3	1	1	118.31	<1	2	1	5
45.793	4	2	0	1	84.957	<1	2	0	4	120.12	1	3	1	4
50.139	13	1	1	2	87.439	<1	3	0	3	121.85	<1	1	0	6
50.622	<1	0	0	3	90.831	2	3	1	2	122.60	<1	4	1	2
54.875	4	2	0	2	92.788	<1	4	0	0	127.25	<1	3	0	5
55.325	2	1	0	3	94.651	1	1	0	5	131.20	<1	1	1	6
57.235	<1	2	1	0	95.119	<1	4	0	1	132.75	<1	5	0	1
59.960	9	2	1	1	96.238	1	2	1	4	134.29	<1	4	0	4
64.036	2	1	1	3	98.751	1	2	2	3	136.42	1	2	0	6
65.786	<1	3	0	0	102.23	<1	1	1	5	137.89	2	4	1	3
67.744	6	2	1	2	102.56	<1	3	1	3	140.31	<1	3	3	0
68.144	7	2	0	3	103.87	<1	3	0	4	143.25	3	5	0	2
68.318	5	3	0	1	104.20	<1	3	2	0	144.11	<1	3	3	1
73.468	2	1	0	4	106.59	<1	3	2	1					
75.660	3	3	0	2	112.11	<1	4	1	0					

Figure 3.9: PDF of Quartz (Source: JCPDS Database available in Institute Laboratory)

X-Ray Diffraction pattern of the sediment was recorded by employing CuK$_{\alpha}$ radiation (λ=0.154056 nm) using X-Ray Diffractometer (Make: Bruker, Model: D8 Advance) (Figures 3.9 and 3.10). Powdered sediment sample was placed on a glass slide which was then mounted on the sample holder of the diffractometer and the sample was scanned in the range 5-70° at a constant speed. The JCPDS database supplied with the diffractometer was used to identify the peaks of minerals in the diffractograms. The peak areas of the mineral species were measured, the areas were normalized to 100% and the value for each mineral was converted to percentages to do a semi-quantitative estimation (Schultz, 1964) of the minerals present in the sediment samples.

Figure 3.10: The X-Ray Diffractometer [Department of Nano-Technology, IIT Guwahati]

3.2.4.2. Report of the results

Results showing diffraction angles and intensity in count per second were obtained in 'Notepad' files. The data were exported to MS-Excel spreadsheets and diffractograms were plotted for identification and quantification of various minerals.

3.2.5. Analyses of metals

3.2.5.1. Sample preparation

Standard Practices for Extraction of Trace Elements from Sediments (ASTM, 2003) were used for determination of extractable concentrations of aluminum, cadmium, chromium, copper, iron, lead, manganese, nickel and zinc in the suspended and bed sediments of the Brahmaputra River. The dried sediment samples should not be ground in such a way to alter the natural particle size distribution. Fracturing a particle disrupts the silicate lattice and makes available those elements which otherwise are not easily digested.

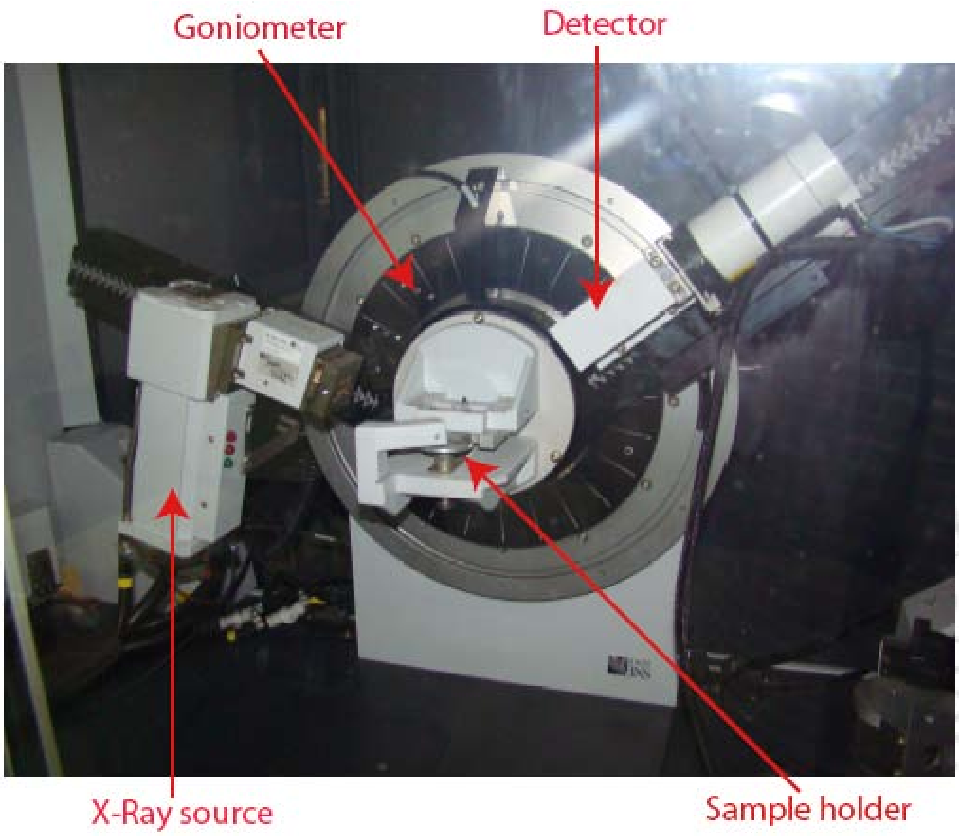


Figure 3.11: Close view of the X-Ray Diffractometer used in mineralogical analyses

Apparatus used for digestion of samples and preparation of standards for various metals are as follows: Glass beakers (50 mL, 250 mL, 500 mL, 1000 mL), ribbed watchglasses, filter papers (Whatman Grade 40), pipettes (1 mL, 5 mL, 10 mL), funnels and funnel stands, volumetric flasks (50 mL, 100 mL, 500 mL, 1000 mL), specimen tubes (100 mL), distilled water laboratory bottle (1000 mL) and reagent bottles. All glasswares used were of borosilicate glasses.

Reagent grade chemicals and deionised water were used in the experiments. Concentrated hydrochloric (Sp. Gr. 1.19) and concentrated nitric (Sp. Gr. 1.42) acids, low in metallic ions, were used in the digestion process. Stock solutions of metals were prepared from pure metal strips or reagent grade compounds of the metals.

All glassware and other containers were thoroughly cleaned by soaking in detergent followed by soaking in 10% HNO_3 for 48 hours and finally rinsed with deionised water several times prior to use.

4 g (weighed nearest to 0.1 mg) of dried bed sediment samples was placed in 250 mL beakers (Due to low amount available, 1 g of suspended sediment was used with necessary correction in the calculation.). An empty beaker was included in each analysis set as a reagent/glassware blank. Following were added to each beaker (including the empty one) in order: 100 mL of water, 1.0 mL of concentrated HNO_3 (sp. gr. 1.42) and 10 mL of concentrated HCl (sp. gr. 1.19). Presence of carbonates causes a foaming reaction on addition of concentrated HNO_3, which requires slow addition of acids. The beakers were covered with ribbed watchglasses and heated on a hot plate at 95 °C. The solutions were not allowed to boil to prevent splattering. When the solutions were reduced to 10-15 mL, the beakers were removed from the hot plate and were allowed to cool to room temperature. Each solution was filtered and quantitatively transferred to a 50-mL volumetric flask and diluted to volume. Concentration (C) of each of the nine metals taken up in this study was found out with the help of an atomic absorption spectrophotometer. The calculations were carried out as follows:

$$C = [(Q-S) \times V] / U$$

where Q = concentration of the element in the digested solution (μg/mL); S = concentration of the trace element found in the reagent/glassware blank (μg/mL); V =

volume of extract (50 mL); U = weight of the sample corrected to a dried sample at 105 °C (g); C = trace element per gram of dry sample (μg).

3.2.5.2. Description of the instrument

The atomic absorption spectrophotometer used for metal analysis was Spectra AA-55B manufactured by Varian (Figure 3.11).

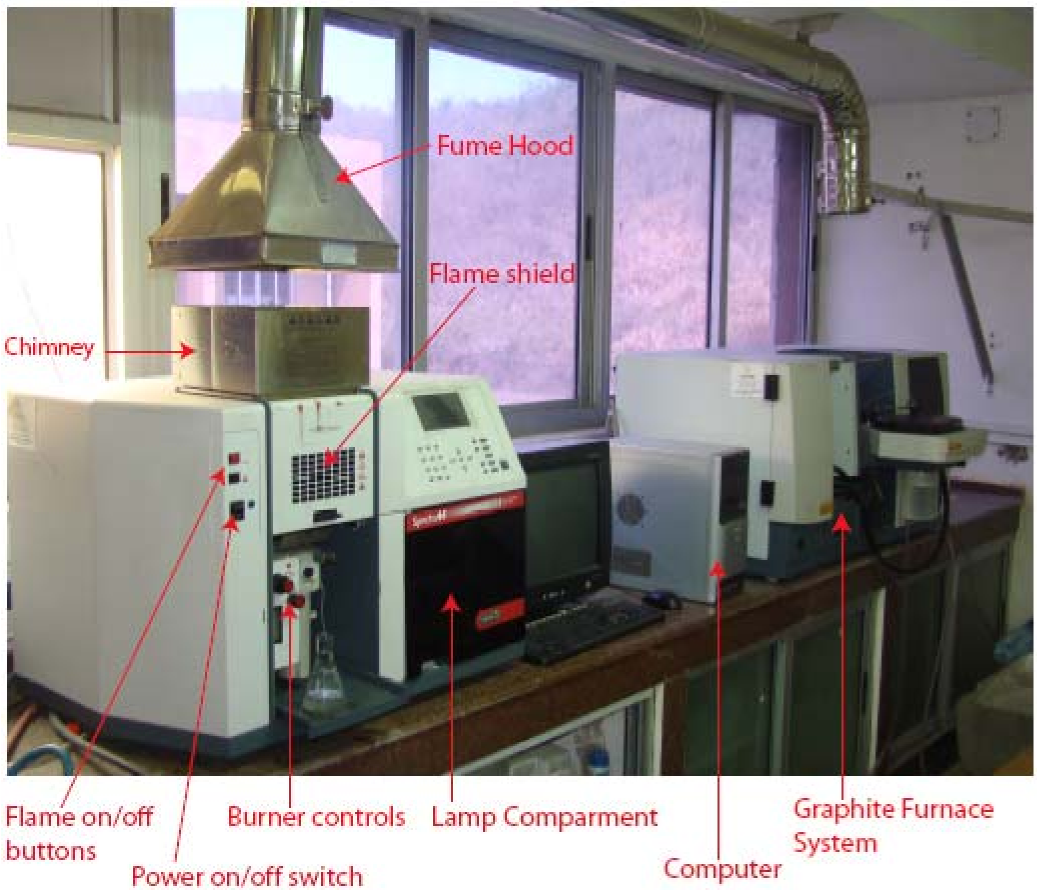


Figure 3.12: The Atomic Absorption Spectrophotometer (Varian) used in metal analyses at the Civil Engineering Department Laboatory, IIT Guwahati

Its features include:

- Automatic monochromator, slit width and gas selection
- Two fixed hollow cathode lamp positions with manual selection lever
- Universal mark 7 spray chamber / nebulizer with mark 7 burner

The results were analyzed by Spectra AA windows software.

3.2.5.3. Principle involved

The basis of atomic absorption spectrometry (AAS) is the absorption of discrete wavelengths of light by ground state, gas-phase free atoms. Free atoms in the gas phase are formed from the sample by an "atomizer" at high temperature. When a solution of acid digestate is introduced into a high-temperature flame, molecules containing the elemental atoms will eventually become gaseous atom through a series of reactions.

Figure 3.12 is an illustration of these reactions when calcium (Ca) is analyzed. Removal of water (desolvation) from aqueous $CaCl_2$ solution produces gaseous $CaCl_2$, which is further dissociated into gaseous atom (Ca^0). At an elevated temperature, Ca can have other electronic configurations, including Ca^{0*} (excited vapour Ca atom), Ca^+ (ionic Ca), and Ca^{+*} (ionic Ca with an excited electron). In the analysis of Ca by atomic absorption spectroscopy, radiation absorption of gaseous atom (Ca^0) is measured Reactions leading to the formation of gaseous atoms (Ca^0) are the desired reactions. All other reactions (Reactions 4-8) are undesired and will result in interferences. Effect of temperature on the ratio of excited atoms and unexcited (ground state) atoms is quantitatively described by Boltzmann equation:

$$N^* / N = (P^* / P)\, e^{-(E^*-E) / kT}$$

where N^* and N are the number of atoms in an excited state and the ground state respectively, k is the Boltzmann constant (1.38×10^{-23} J/K), T is the temperature in Kelvin, E^*-E is the energy difference between the excited state and the ground state. The P^* and P are the statistical weights of the excited and the ground states respectively, which can be determined by the number of states having equal energy at each quantum level n.

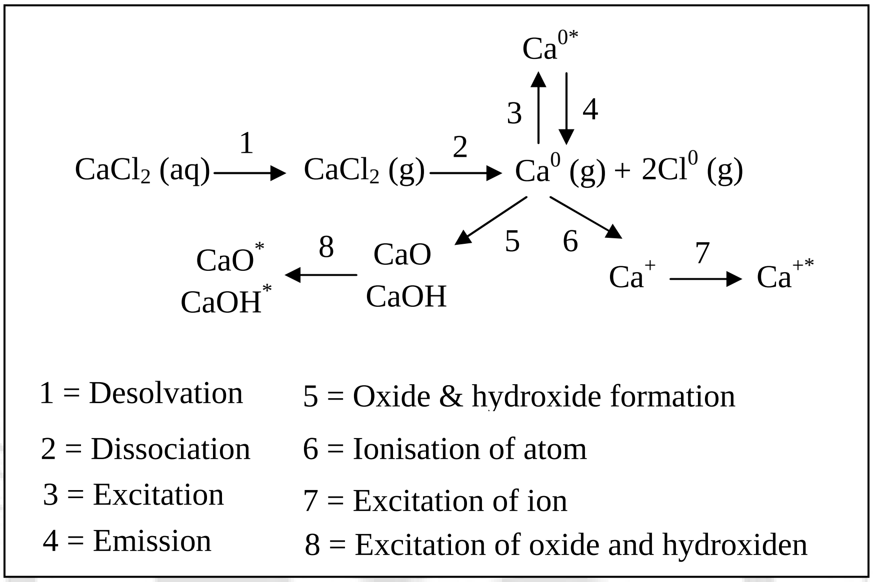


Figure 3.13: Process occurring in a flame for a solution containing $CaCl_2$ (Christian, 2004 as quoted by Zhang, 2007)

Atomic absorption occurs when a ground-state atom absorbs energy in the form of light of a specific wavelength and is elevated to an excited state. The amount of light energy absorbed at this wavelength increases as the number of atoms of the selected element in the light path increases. The relationship between the amount of light absorbed and the concentration of analyte present in known standards can be used to determine unknown concentrations by measuring the amount of light absorbed. Instruments readouts can be calibrated to directly display concentrations.

AAS is an elemental analysis technique capable of providing quantitative information on ~70 elements in almost any type of samples. The result gives total quantity of a metal (existing in various forms like chloride, sulfate, nitrate, complex, or organometallic compound) and does not depend upon the chemical forms of the metal. Very low concentrations, up to ppt level, can be determined by AAS. Another principal advantage is that a given element can be determined in the presence of other elements, which do not interfere by adsorption of the analyte wavelength. Therefore it is not necessary to separate the analyte from the rest of the sample (the matrix). The major disadvantages of AAS are that no information is obtained on the chemical form of the analyte (no "speciation") and that often only one element can be determined at a time.

3.2.5.4. Analysis

Stock standard solution of 1000 ppm was prepared for each element according to Varian's instruction manual for atomic absorption spectrometry. Stock solution of an element was diluted for preparing a series of working standards which were used to make calibration curve for that element. Unknown concentration of a solution was determined by using the part of the calibration curve where relationship between absorbance and concentration was linear. The steps involved in the analysis are as follows:

- The sample/standard is aspirated to the burner chamber. The sample becomes an aerosol and mixes with the fuel and the oxidant gases. The metals remain dissolved in the aerosol.
- The aerosol droplets move into the heat of the flame (2000-8000 °K), where the solvent is evaporated and the solid particles gets atomized (broken into atoms).
- A light beam from a lamp (Hollow Cathode Lamp, HCL) whose cathode is made of the element being determined is passed through the flame into a monochromator and a detector. Free, unexcited ground-state atoms of the element absorb light at characteristic wavelengths; this reduction of the light

energy at the analytical wavelength is a measure of the amount of the element in the sample.

- Result analysis is done through Spectra AA windows software.

3.2.5.5. Report of the results

The report of the results contains the method of analysis (e.g., Flame Ionisation), the calibration curve, concentrations of the elements (in mg/L) and the mean absorbance produced by them. The observed concentrations should lie in the linear range of the calibration curve for accuracy of the results. Observations falling outside the linear range do not give correct concentrations and should be rejected.

3.3. Resource limitations

Secondary data on the Brahmaputra River are scarce. Research too has been limited. All primary data had to be first generated by the scholar, although such efforts require strong institutional support and difficult to be done individually in India due to limited advanced sampling tools and logistics like vessels etc. Due to strong turbulence in the rivers during most part of the year, sampling by boat was not possible. Hence, sampling was done from the top of the only railway bridge near the sampling site. Due to constant movement of trains, permission to carry out sampling from the bridge was possible for only limited time. Therefore, to improve the database, all available data (up to 15-10-2008) from CWC were collected additionally. There were other resource limitations like long waiting time for sample analyses due to single instrument (e.g. Laser Particle Analyse) being available for that purpose and best possible efforts were put to overcome them. A substantial time of the work had to be spent on these efforts.

CHAPTER 4

DISCHARGE AND SUSPENDED SEDIMENT CHARACTERISTICS OF THE BRAHMAPUTRA RIVER

4. Introduction

Various factors are responsible for the high volume of sediments in the Brahmaputra River like high intensity of rainfall, easily erodible rocks, frequent landslides, high seismicity, erosion-causing crop practices and erodible nature of the bank materials (Bora, 2004, Datta and Singh, 2004).

4.1. Discharge

CWC data (from June 2001 to October 2008) reveals that the discharge during this period had ranged from 2,031 m^3/s (14th February 2005) to 55,235 m^3/s (22nd July 2004). The low values usually occurred during February or March, but maximum discharge occurred in July, August or September. Datta and Singh (2004) reported occurrences of similar minimum flows during late February to early March. About 65% of the annual discharge occurs during the monsoon months (June to September) and the remaining 35% is distributed in the remaining part of the year (Figure 4.1). Monthly variations in mean discharges are shown in Figure 4.2.

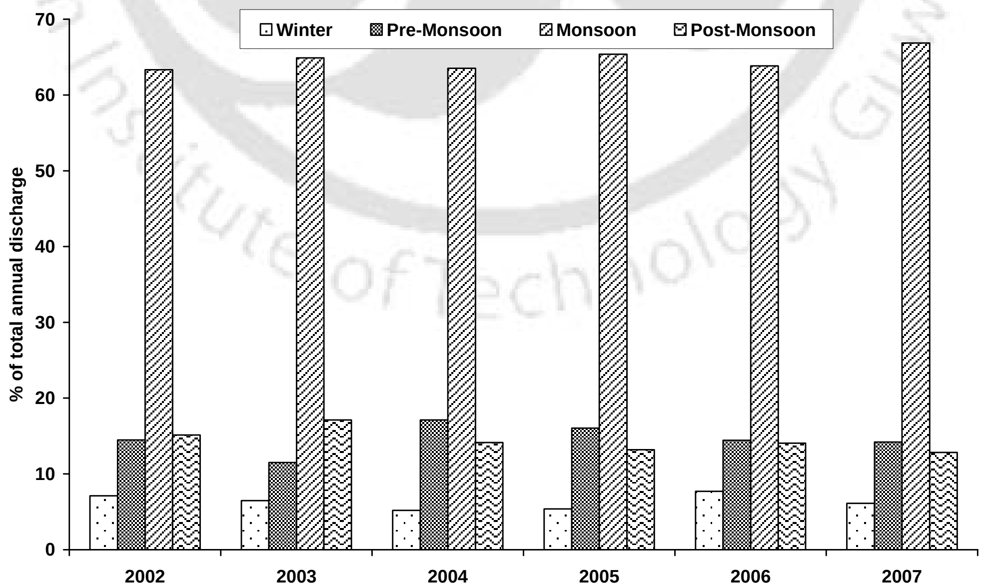


Figure 4.1: Seasonal variation of discharge

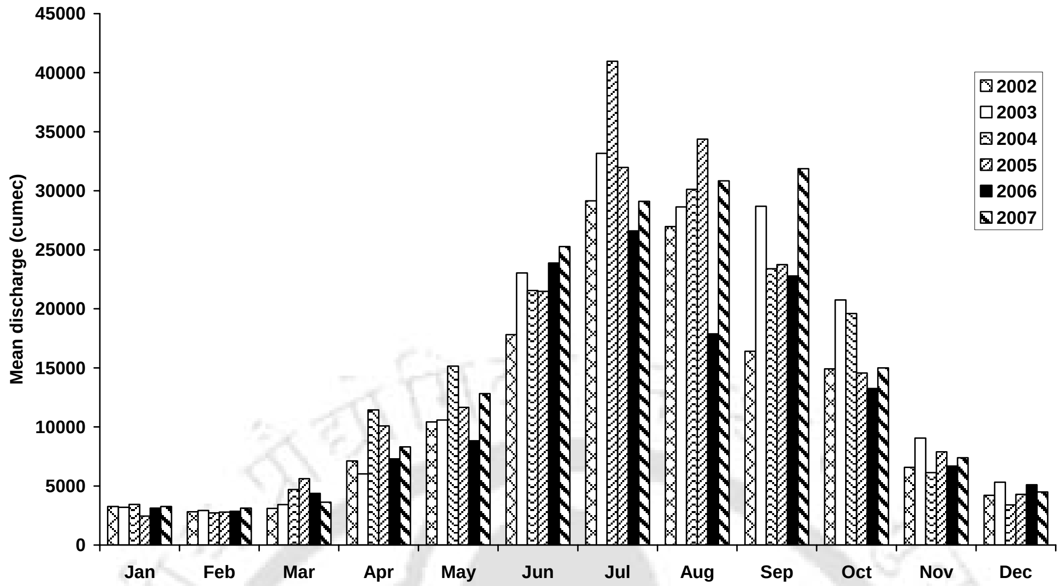


Figure 4.2: Variation of monthly mean discharge

Monthly mean discharge ranged from 2,450 m^3/s (January 2005) to 40,975 m^3/s (July 2004). These observations can be related to the duration of rainfall occurring in the catchments. The basin experiences 65-80% of the average annual rainfall during the monsoon months (Jain et al., 2007).

4.2. Suspended sediment concentration

Discharge and suspended sediment concentration (SSC) in the Brahmaputra River peak almost synchronously (Figure 4.3). Similar pattern was observed in the annual flow and sediment discharge hydrographs of the Brahmaputra River for the years 1971 to 1979 (Goswami, 1985). Increase in sediment concentration with discharge is evident from the graph (Figure 4.4). Synchronous increase of sediment load with discharge of the Brahmaputra River was also exhibited by the data collected at Bahadurabad (Coleman, 1969). Jiongxin (1998) observed similar relationship between sediment transport rate and water discharge shown in a plot based on data from 100 alluvial rivers of China.

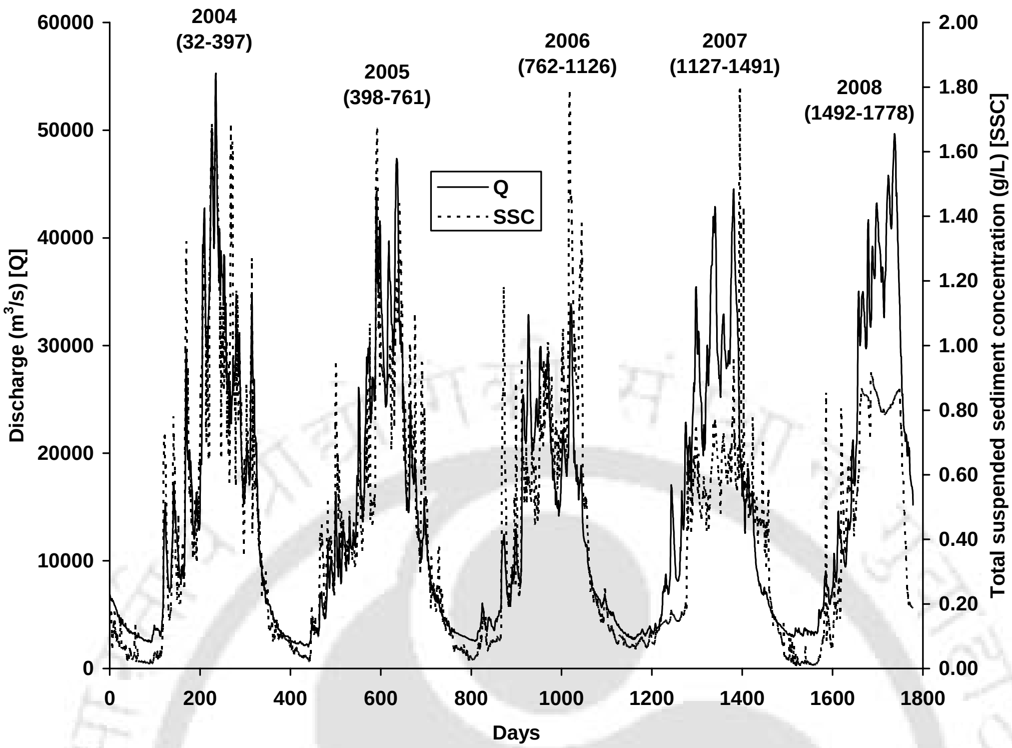


Figure 4.3: Daily variation of discharge and suspended sediment concentration

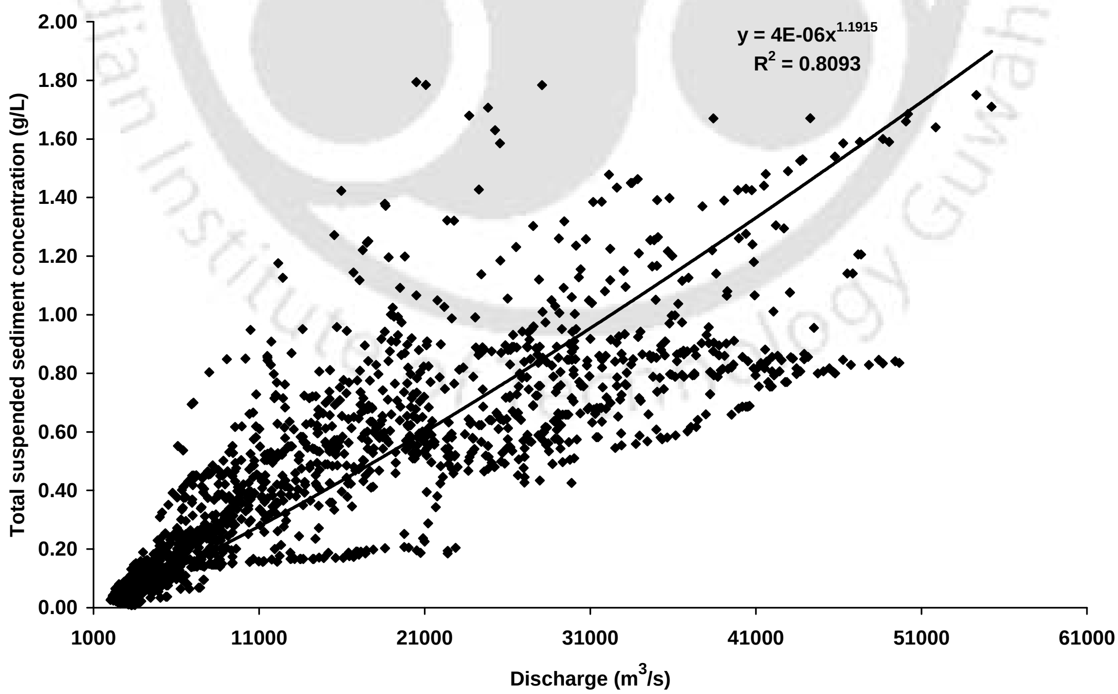


Figure 4.4: Discharge versus total suspended sediment concentration

Increased stream power at higher discharge enables a river to carry more sediment load (Goswami, 1985).

'Top Water Layer Suspended Sediment' (TWLSS) concentrations (average of five equally spaced cross sectional samples) determined in the present study was plotted against discharge of corresponding dates (Figure 4.5).

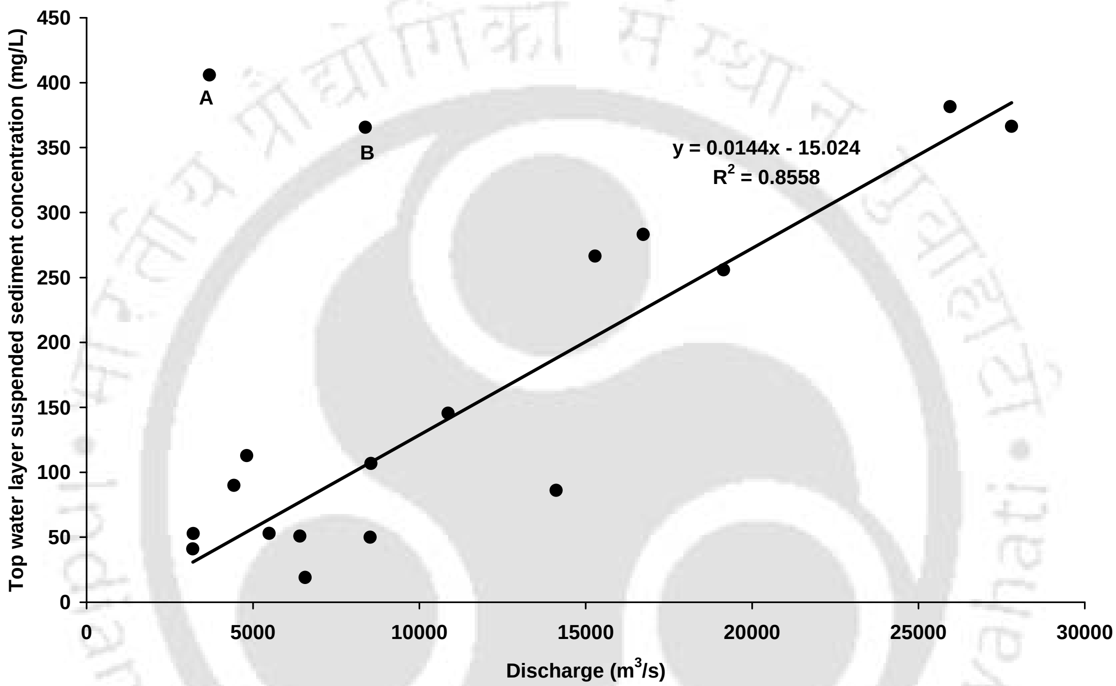


Figure 4.5: Discharge-Top water layer suspended sediment concentration curve

This plot shows increasing relationship between sediment concentration and discharge, the TWLSS concentrations determined in the present study belonging to the top 50-100 cm surface water layer of the river, representing mainly the wash load. Points A and B are two influential observations in the data set. There is a high degree of linear correlation ($R^2 \approx 0.86$; $p<0.0001$) between discharge and TWLSS concentration if these influential observations are excluded. However, these perhaps should not be considered as outliers or measurement errors or recording errors, as discharge and sediment concentration relations were found to exhibit hysteretic behaviour in the Brahmaputra River (as can be seen from Figures 4.6-4.9 reported later).

The plot of discharge against suspended sediment concentration (Figure 4.4) reveals a high degree of scatter, so hysteresis loop was examined to explore the associations between these variables (Wood, 1977; Rieger et al., 1988). The plots of monthly mean discharge (Q) against monthly mean suspended sediment concentration (C) in the Brahmaputra River are shown in Figures 4.6 to 4.9. In these figures, the months January to December have been denoted by the numbers 1 to 12 respectively. Sediment rating curves often exhibit hysteretic behaviour, as seen in these figures.

Williams (1989) described various types of C-Q relations with graphical explanations and providing physiographic or hydrological reasons for these. According to him, depletion of available sediments or formation of an armoured layer prior to occurrence of the peak discharge results in clockwise hysteresis. Differences in travel time between sediment and water peaks (relevant for large basins), combination of highly erodible soil and prolonged erosion during the flood, and seasonal variability of rainfall distribution and sediment production are some of the causes for sediment peaks falling in recession limb of the hydrograph, thereby resulting in anti-clockwise hysteresis. Tarazon et al. (2009) states that clockwise loops are caused by sediment accumulated near the catchment outlet, while counterclockwise loops are related to sources supplying sediment from remote places. Heidel (1956) suggested that the maximum sediment concentration usually occurs prior to peak discharge if the stream was small. According to Goswami (1988), the peak of the sediment load precedes the discharge peak due to high concentration of relatively fine sediments. Clockwise portion of the C-Q relation (Figures

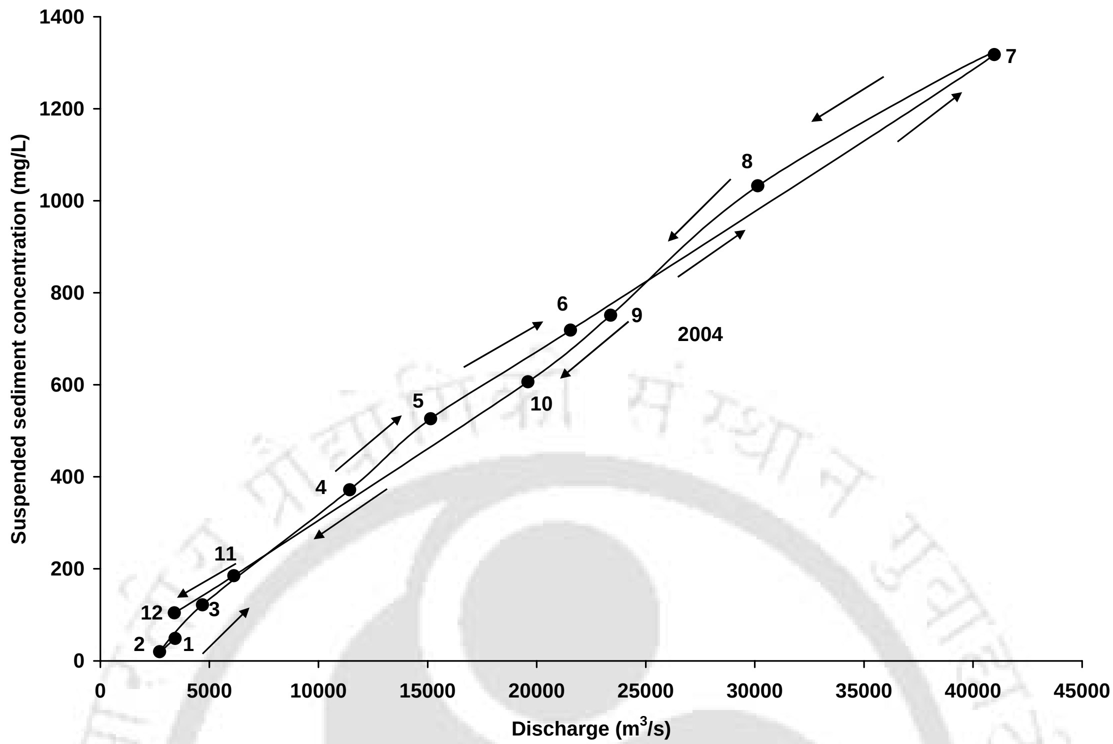


Figure 4.6: Figure-eight C-Q relation in 2004

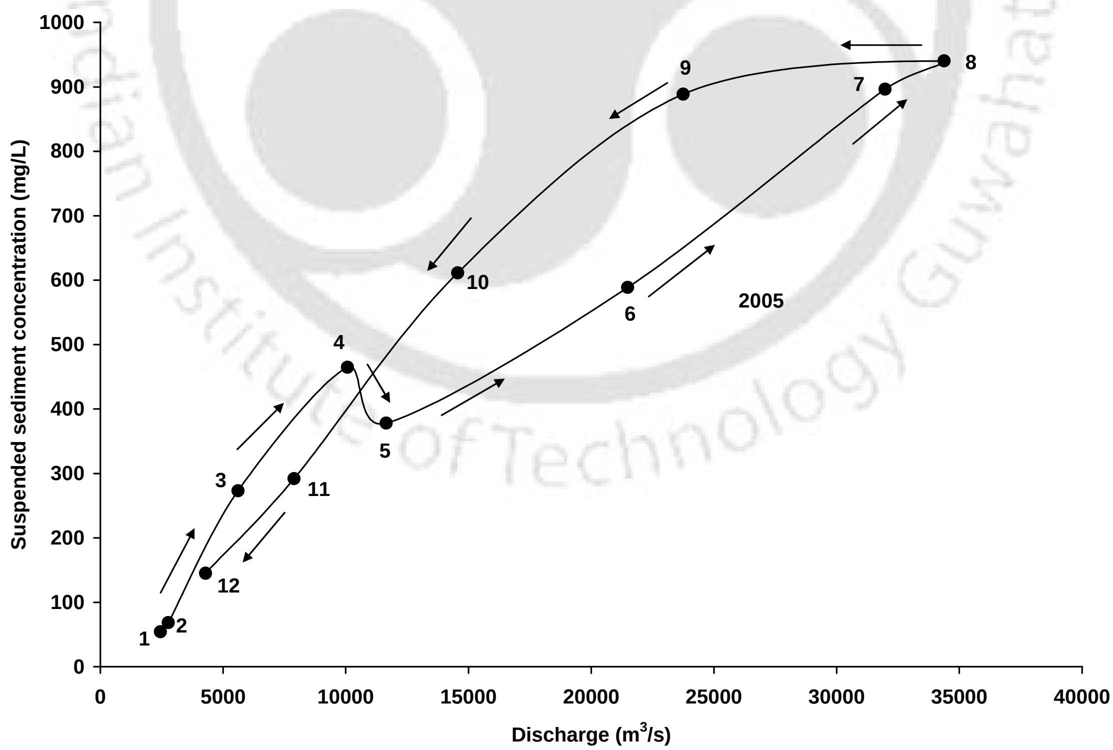


Figure 4.7: Figure-eight C-Q relation in 2005

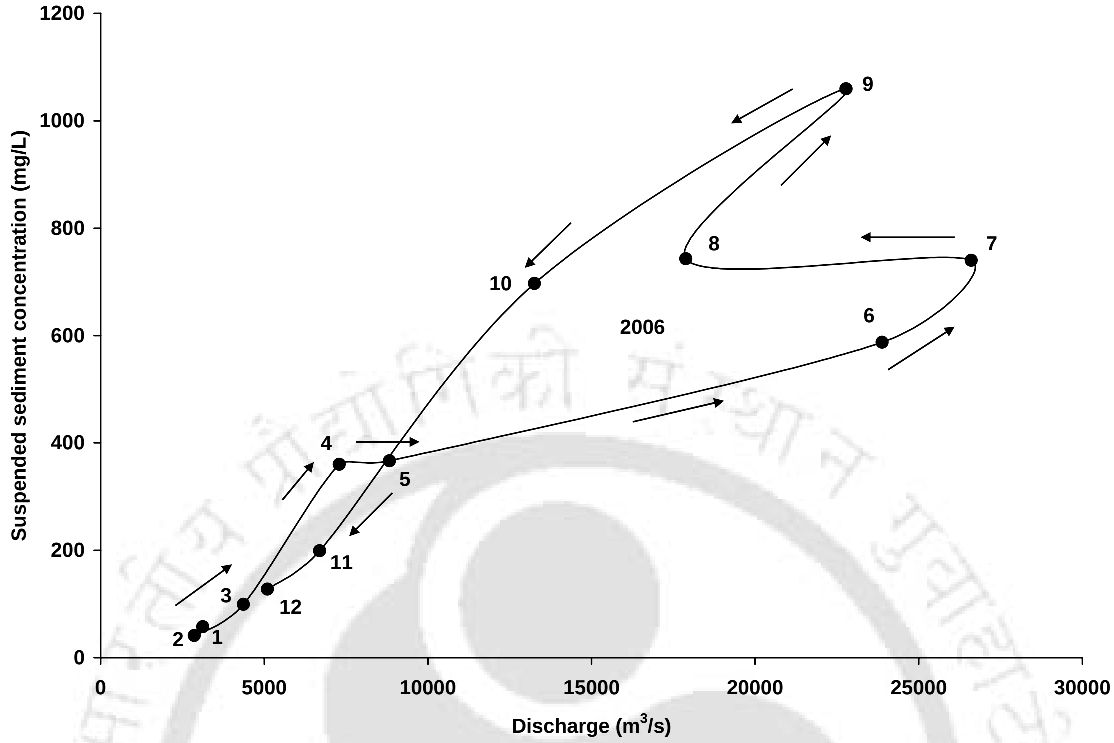


Figure 4.8: Figure-eight C-Q relation in 2006

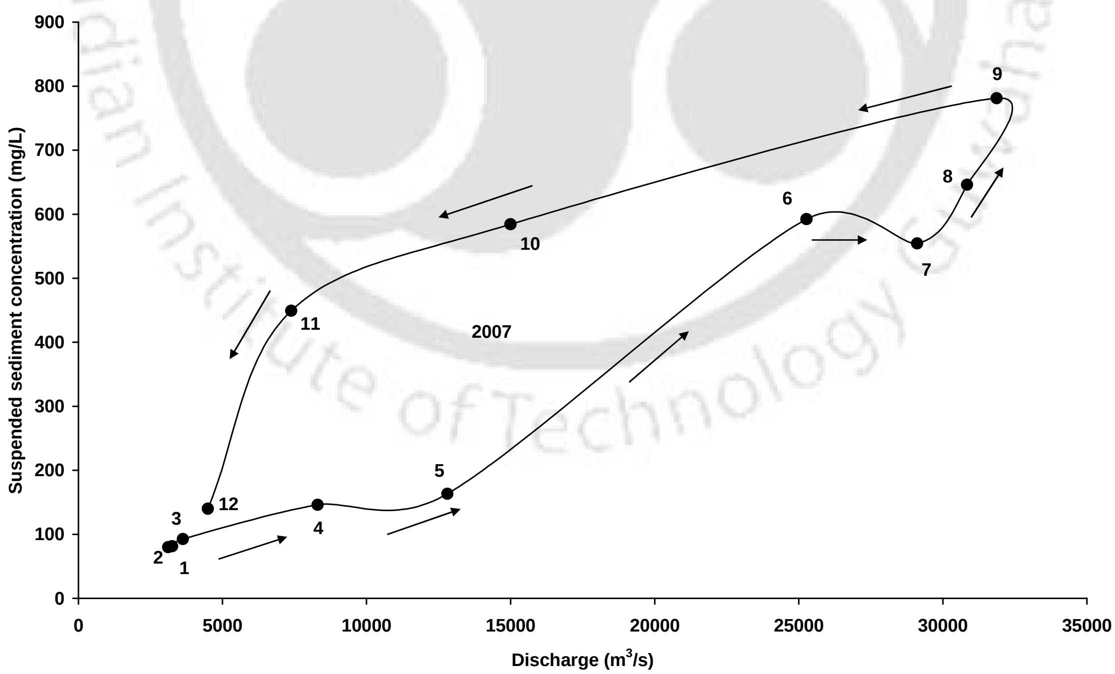


Figure 4.9: Counterclockwise-loop C-Q relation in 2007

4.6, 4.7, 4.8) may be due to high concentration of fine sediments and the anticlockwise portion may be due to large distances of some sediment sources from the measuring site. Williams (1989) reports that changes in water discharge tend to follow wave velocity while suspended sediment tends to travel at a velocity closer to the mean flow velocity. Since wave velocity is faster than mean flow velocity, discharge peaks before sediment does, forming counterclockwise loop in C-Q relation. It is interesting to note that the plot between sediment load and discharge of Brahmaputra at Bahadurabad (Coleman, 1969) also results in figure-eight shape (Appendix-I). It is reported in various isotopic studies (Singh and France-Lanord, 2002; Singh et al., 2003) that half of the sediments delivered to the Brahmaputra are supplied by the Siang River (its major constituent in the upstream, which is the name given to Tsangpo after entering India), while the Himalayan and the other eastern tributaries account for 40% and 10%, respectively. Seasonal variability of rainfall (Jain, 2007) and distance of the major sediment sources from the sampling sites are the likely causes of the counterclockwise loops in C-Q relation depicted in figures 4.6 to 4.9. Singh et al. (2007) observed a counterclockwise loop in the sediment-discharge relationship in the Ganga River, which is also a Himalayan River like the Brahmaputra. Major fluctuations in both flow and sediment load occurs in the Brahmaputra River during the monsoon period (Goswami, 1985) which may give rise to many loops in the C-Q plots (Figure 4.6).

Figures 4.10 and 4.11 show C-Q relations in a rising limb and a falling limb of hydrographs of the Brahmaputra River. While C-Q relation shows random fluctuations in the rising limb of the hydrograph, it shows a uniform decrease in its falling limb.

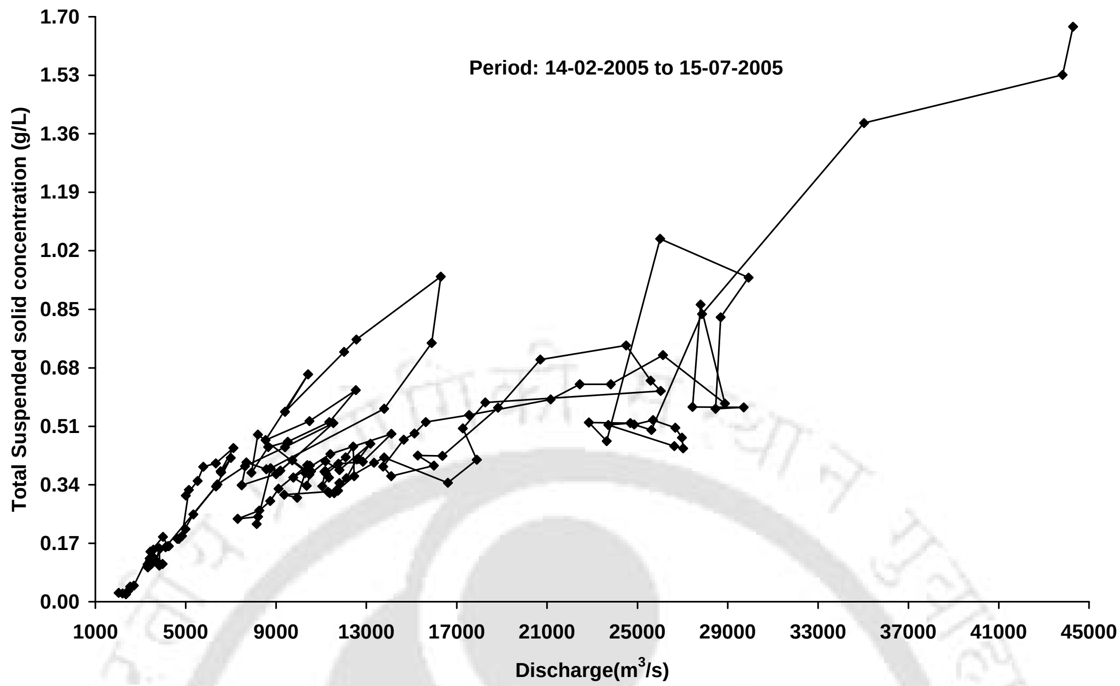


Figure 4.10: Suspended sediment concentration-Discharge relation in a rising limb of hydrograph

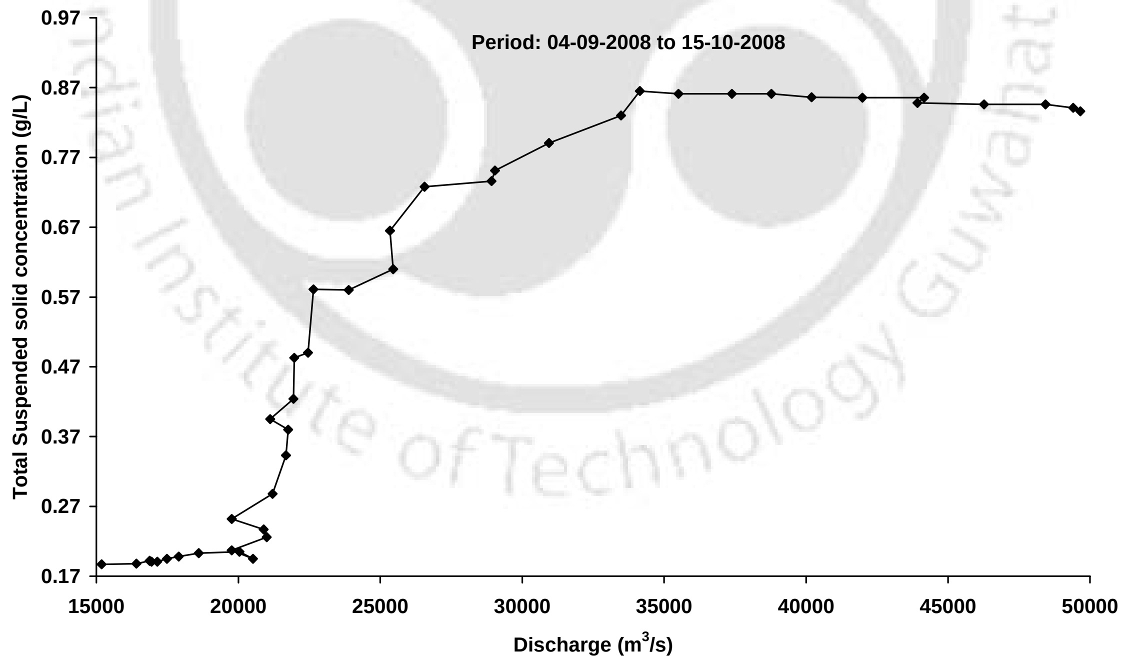


Figure 4.11: Suspended sediment concentration-Discharge relation in a falling limb of hydrograph

According to Singh (1992), sediment concentration decreases with the stream flow recession generally at a less rapid rate than the increase during the rising stage and has a long tail. He also reports that the concentration often fluctuates erratically during the rising limb, but decreases uniformly during the falling limb. Similar behaviour has been observed in case of the Brahmaputra River at the study site (Figure 4.10, 4.11). The falling limb C-Q relation (Figure 4.11) has also exhibited characteristics of counterclockwise loop. Proportionate reduction of concentration with discharge (Figure 4.11) may not occur due to flowage failure of river banks (Coleman, 1969).

Figure 4.12 and 4.13 show the cross-sectional and temporal variations of TWLSS concentrations carried in the top 50-100 cm of the water layer of the Brahmaputra River.

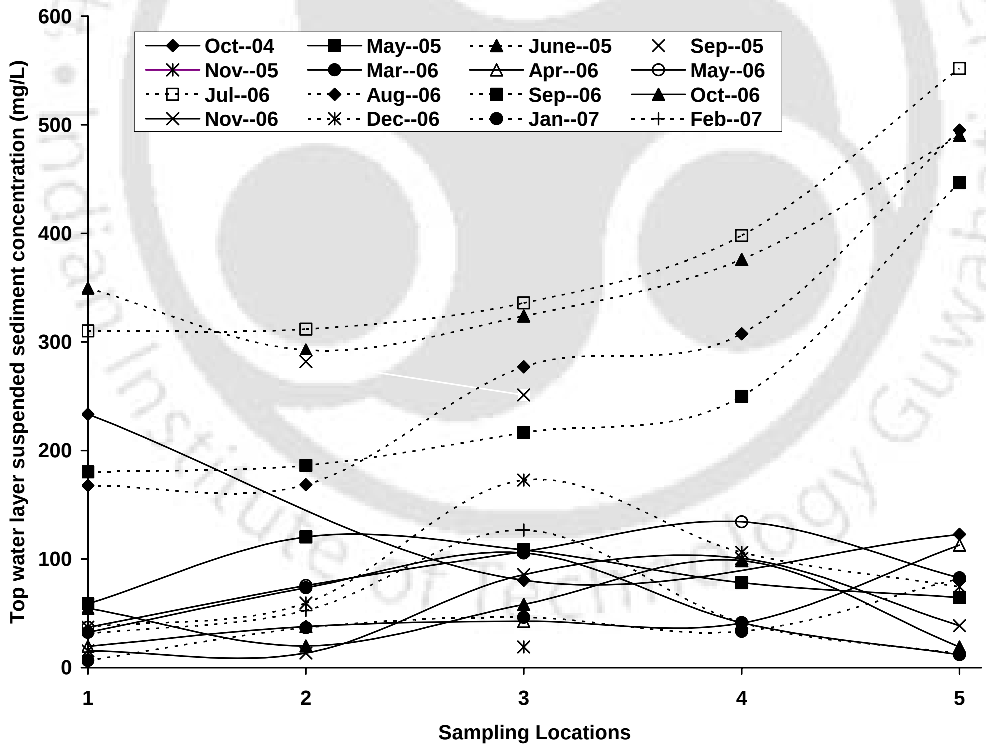


Figure 4.12: Cross-sectional variation of Top water layer suspended sediment concentration

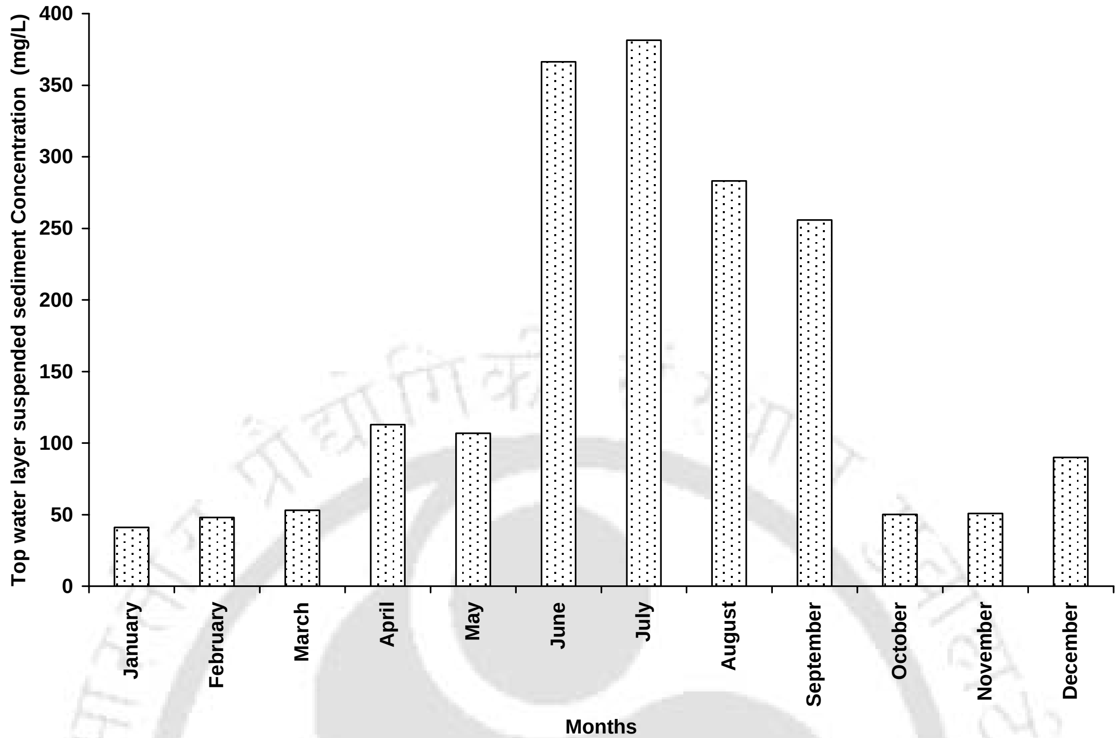


Figure 4.13: Monthly variation of Top water layer suspended sediment concentration

During monsoon months (June to September), a rising trend is seen towards south bank of the river which is likely to be due to incomplete mixing of tributary waters, local eddies, etc. Limited conclusions can be drawn unless relevant data from the tributaries or local eddy conditions are monitored. It is worth mentioning here that a small tributary (the Bharalu) joins the river at about 2 km upstream of the sampling location. Parsons et al. (2008) cited various references (Mackay, 1970; Krouse and Mackay, 1971; Stallard, 1987; Gaudet and Roy, 1995) to report that complete mixing of flows where two large rivers join, requires a significant river length, which can often extend to tens or often even hundreds of kilometers.

Figure 4.13 shows that TWLSS concentrations are very high in the monsoon months. High rainfall in these months (Jain et al., 2007) increases the sediment yield (Ludwig and Probst, 1998) resulting in higher sediment concentrations.

Estimates of sediment load (daily, monthly, seasonal, annual) have been made using CWC data following the method described by Charlton (2008). The annual estimates of suspended loads are observed to be 410 million tons in 2004, 327 million tons in 2005, 246 million tons in 2006, and 245 million tons in 2007. Although these values show a decreasing trend, the total sediment load up to 15th October in the year 2008 comes out to be 310 million tons. Goswami (1985) reported that bedload constitute 5-15% of the total load in the Brahmaputra River. Considering this, the total annual sediment loads of the Brahmaputra River approximately fall in the range 259-483 million tonnes, i.e. 445-832 tons km^{-2}.yr^{-1} (Basin area=5,80,000 km^2). Goswami (1998) reported a value of 804 tons km^{-2}.yr^{-1} at Pandu (Guwahati), which is about 200 m upstream of the sampling site of CWC. Daily, monthly and seasonal transports of sediment loads in the Brahmaputra River are shown in Figures 4.14 to 4.16. It can be seen that more than 8 million tonnes of sediment may be transported in a single day during peak transport. More than 80% of the total annual load is transported in monsoon months (June to September).

Sarma (2005) reported the coefficients of variation of mean annual flow and sediment discharge for the period 1971-79 as 0.15 and 0.85 respectively. Coefficients of variation of these two parameters for the CWC data (from December 2003 to October 2008) are found to be as in Table 4.1.

Table 4.1: Coefficients of variation of mean annual flow and sediment discharge

Category	Coefficient of variation	
	Discharge (m^3/s)	Sediment discharge (t)
Daily	0.83	1.36
Monthly mean	0.78	1.17
Annual mean	0.10	0.26

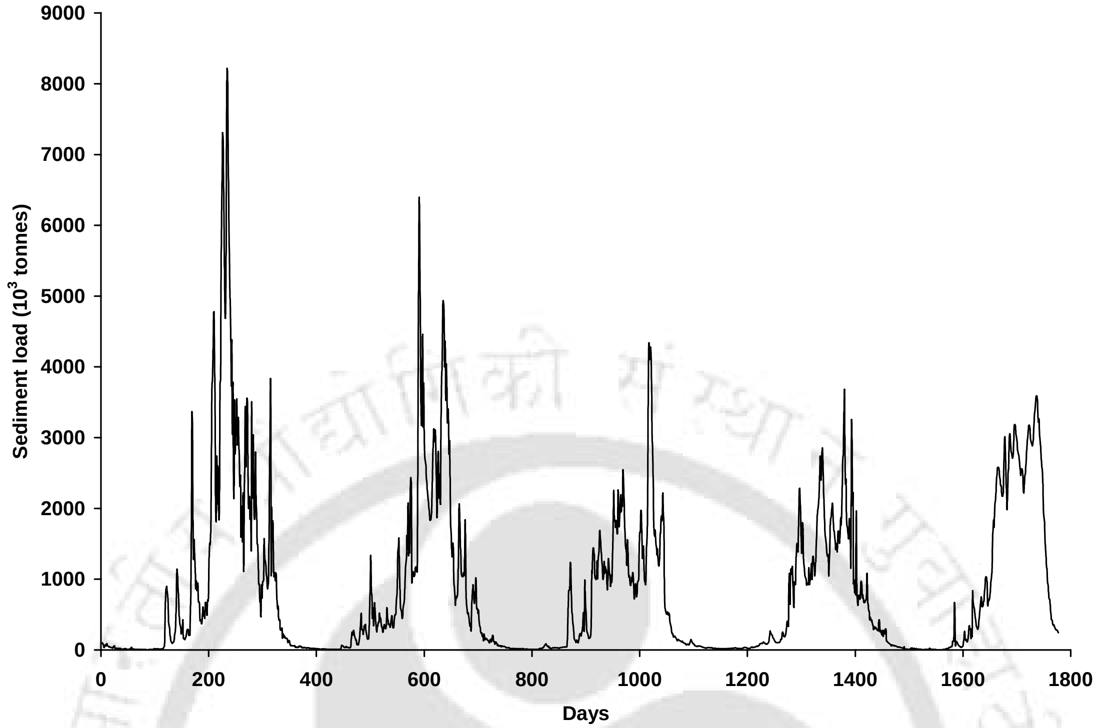


Figure 4.14: Daily suspended sediment discharge hydrograph

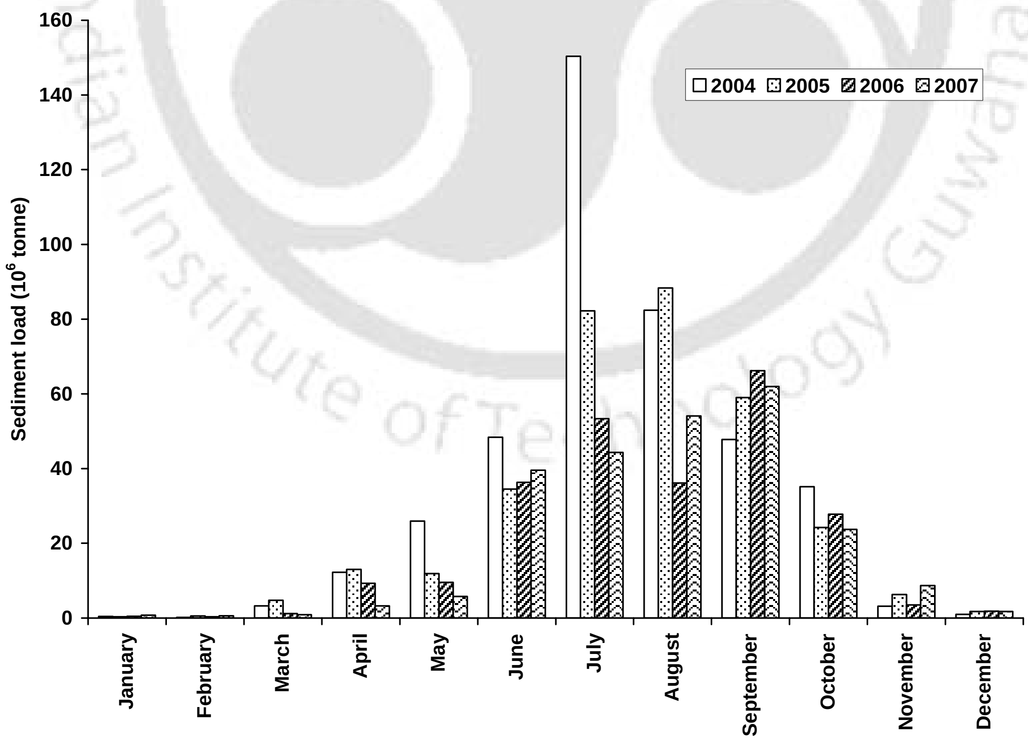


Figure 4.15: Monthly suspended sediment transport

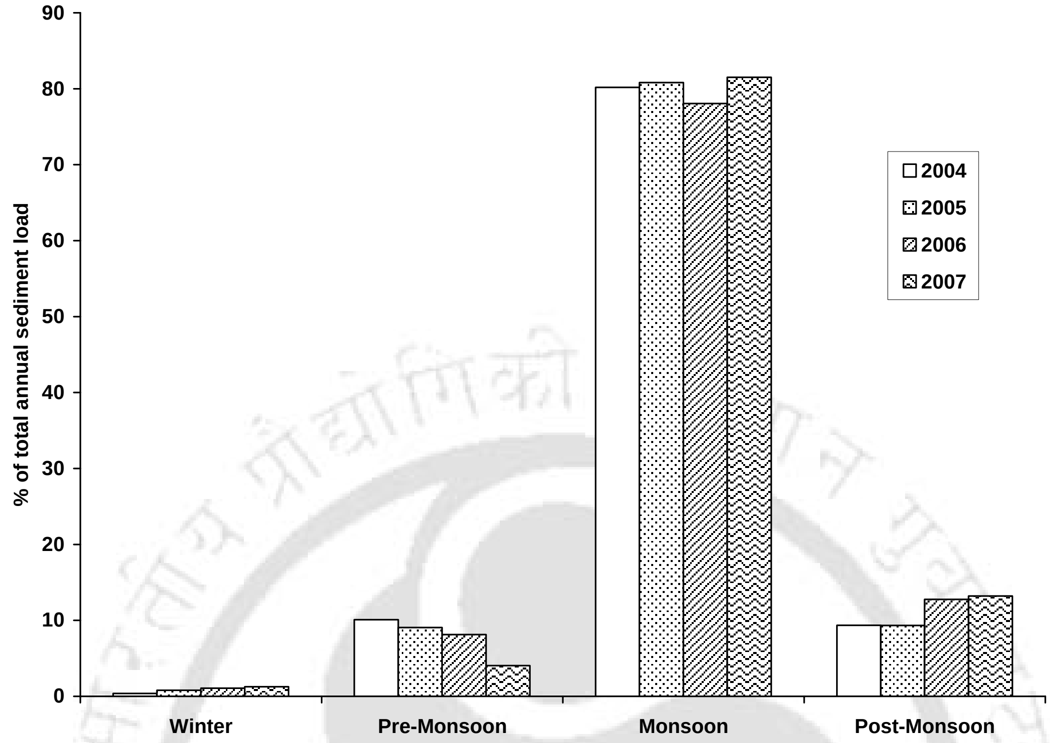


Figure 4.16: Seasonal transport of suspended sediments

Annual variabilities of flow and sediment discharge for the CWC data are considerably lower (particularly for sediment discharge) than the values reported by Sarma (2005). Unless possible variations in sampling methods or changes in the factors controlling these two parameters in the River are examined carefully, it is difficult to comment on the reasons. Further studies are necessary to ascertain the causes of these apparent disagreements.

4.3. Summary

It was observed in the present study that about 65% of the total annual discharge of the Brahmaputra River occurred in the monsoon months (June to September). Annual sediment loads of the Brahmaputra River lied approximately in the range of 445 to 832 tons $km^{-2}.yr^{-1}$ at the sampling sites. More than 80% of the total annual suspended sediment loads was transported during the monsoon months. Suspended sediment concentration (C) increases with discharge (Q). C-Q relations usually exhibited Figure-eight form of hysteresis (Williams, 1989) during the period of study, indicating sediment contribution from both nearby and remote sources. Similar pattern of C-Q relation was exhibited at Bahadurabad (Bangladesh) by Coleman's (1969) data indicating uniformity in sediment-discharge relationship in the downstream of the sampling sites. Large fluctuations were observed in both flow and sediment load of the river, which was revealed by C-Q plots. Suspended sediment concentrations during monsoon months showed increasing trends towards south bank of the river, which might result due to slow cross-channel mixing of tributary inputs of sediments or different hydrodynamic conditions prevailing in this side of the river.

CHAPTER 5

PARTICLE SIZE CHARACTERISTICS OF BRAHMAPUTRA SEDIMENTS

5. Introduction

Particle size characteristics of the Brahamputra River sediments were examined by analyses of 53 TWLSS and 5 bed sediment samples, and CWC particle size data. As the focus of the study was on evaluating the suspended load, limited number of bed sediment samples were investigated primarily to examine the contrast with the suspended sediments. CWC data were classified in three groups in terms of concentrations (g/L) of fine (< 75 µm), medium (75-200 µm) and coarse (>200 µm) fractions of the sediments. The data was not accompanied by particle distribution curves. The grain size distribution of sediments depends on the size range of available sediments, its susceptibility to weathering, erosion and transportation, and the impact of turbulence and flow on the sediments.

5.1. Particle size characteristics

Figures 5.1 to 5.3 show the particle size distribution curves for TWLSS and bed sediments of the Brahmaputra River. With few exceptions, the particle size curves showed similar ranges and shapes irrespective of seasonal changes in flow. Approximate range of particle size for TWLSS was 1 to 100 µm, while bed sediment size fell in the range 1 to 1000 µm. The smallest particle size of the bed sediment is slightly greater than 1 µm. TWLSS particle sizes were almost normally distributed, but the distribution for bed sediment sizes was skewed to the coarser sizes. Polymodal curves (Figure 5.2) were also observed for some TWLSS samples collected during monsoon months, indicating contribution from colluvial soil deposits (Zhang and Chen, 2005). Failure of colluvial soil deposits (e.g., landslides) induced by rainfall is a common geohazard in the natural terrain. Many colluvial soils are widely- and/or gap-graded (Zhang and Chen, 2005).

Kanjilal et al. (1970) observed that majority of the Ganga sands were bimodal. They interpreted its cause to be the presence of considerable amount of silt. As silt is a major constituent of Brahmaputra sediments as well (Figure 5.6), occasional introduction of

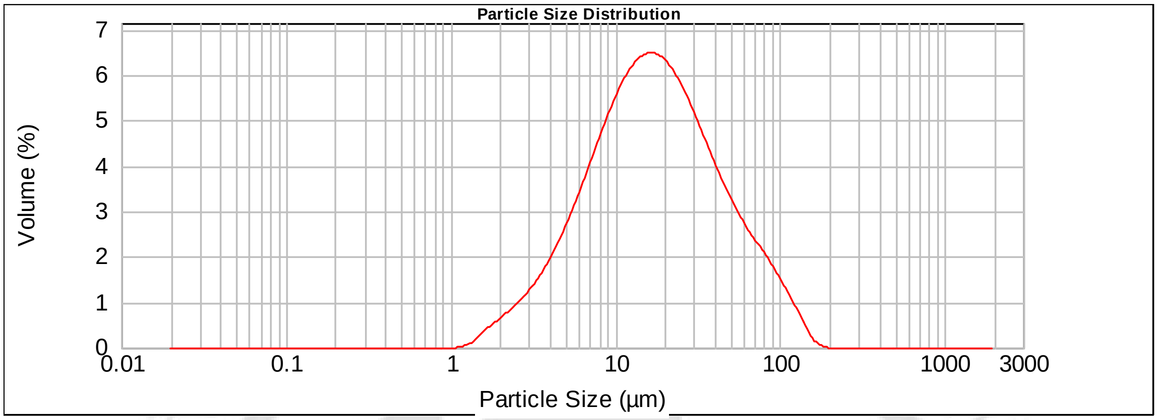


Figure 5.1: Particle size distribution of Top water layer suspended sediment

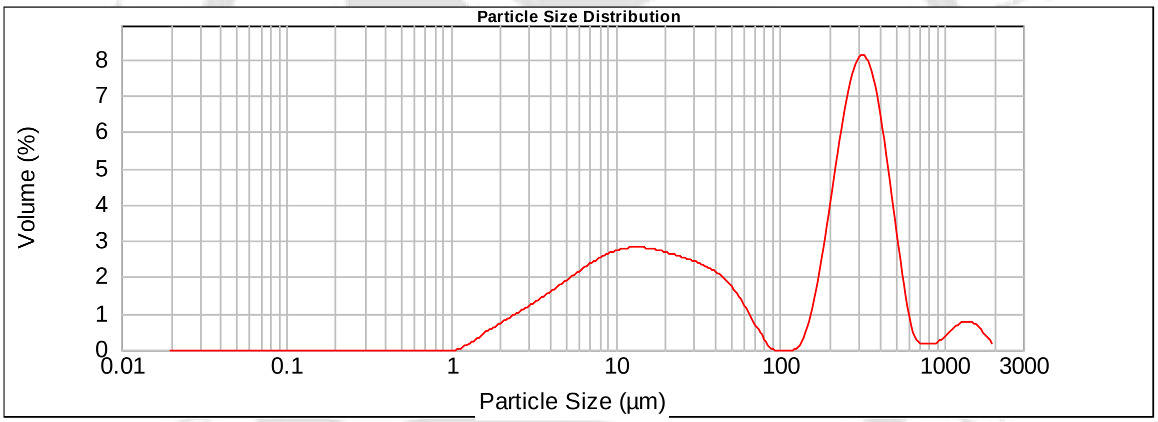


Figure 5.2: Particle size distribution of Top water layer suspended sediment (Polymodal)

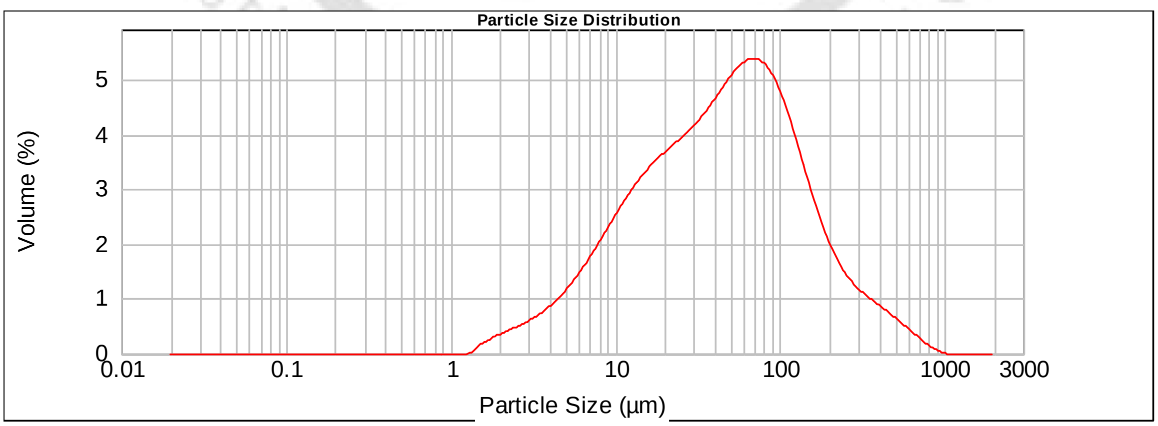


Figure 5.3: Particle size distribution of bed sediments

larger sized sediments into the river through failure of colluvial deposits is likely to produce such bimodal or polymodal curves.

Bed sediment particle size curve (average of the curves for the five bed sediment samples, created with the help of Mastersizer 2000 software) did not show overlapping zone with suspended sediment curves (Figure 5.4), except for a few instances (Figure 5.5).

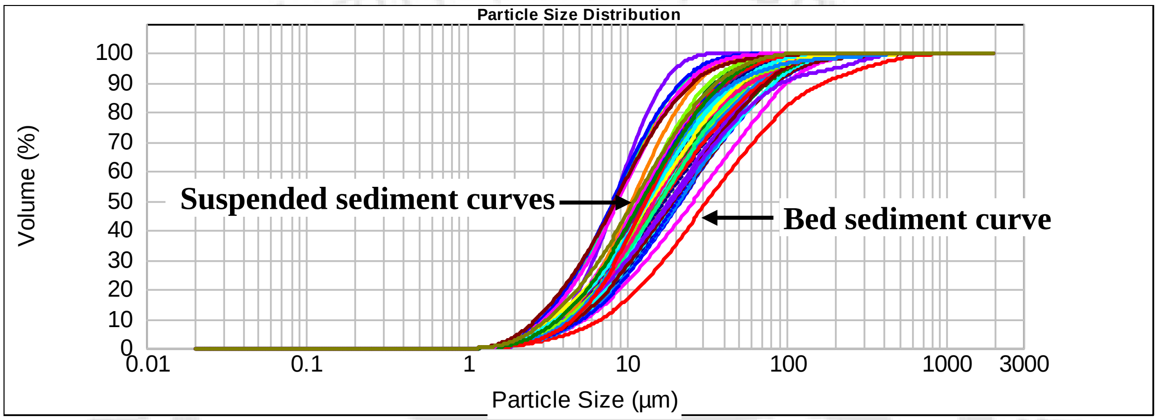


Figure 5.4: Bed sediment and Top water layer suspended sediment curves without overlapping

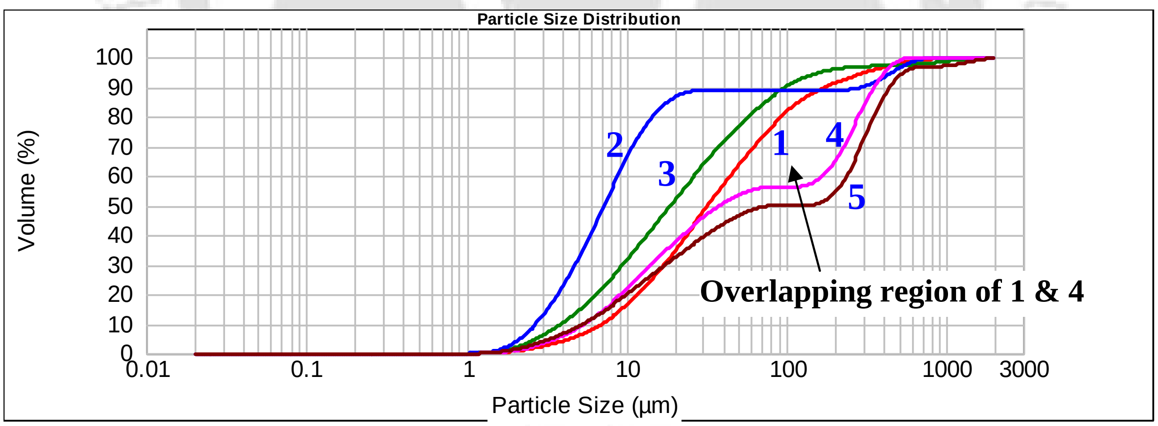


Figure 5.5: Bed sediment and Top water layer suspended sediment curves having overlapping region [Bed sediment (1), TWLSS samples of November (2), March (3) and June (4, 5)]

This indicates that bed sediments coarser than about 200 μm does not generally contribute to the sediment population in the top 1 m (sampling depth) of the water layer (as evident from Figure 5.4) in the Brahmaputra River. Singh et al., 2007 observed that particle size of suspended sediment could exceed 3600 µm in the Ganga River. However, the sampling depth and distance of the sampling locations from the major sources of sediments were not similar for both the cases.

Since more than 90% of the bed sediments are less than 200 µm and TWLSS also contains this size (Figure 5.4), a uniform suspension of this fraction of sediments in the water column of the Brahmaputra River is very much likely, starting right from near the bed. This will indicate either absence of or a thin graded suspension at the sampling site. In the Mississippi River, the uniform suspension is always present, while a graded suspension may be lacking (Singh et al., 2007). Moreover, 80% of the bed sediments belong to TWLSS size range (i.e., less than 100 µm), which further reinforces the conjecture of existence of a thick uniform suspension in the Brahmaputra River at the sampling site. According to Datta et al. (1999), bed sediment resuspension contributes significantly to the suspended load of the Brahmaputra River. This is a likely explanation for majority of both suspended and bed sediments falling into a common size range. However, analyses of more number of bed samples would enable better explanation of this aspect.

Out of 53 size distribution curves, 3 exhibited gap-graded (2, 4, 5 in Figure 5.5) and 1 exhibited widely-graded (3 in Figure 5.5) cumulative size distribution curves. The coarser fractions in these samples should be from nearby sources, which did not get required time to settle out due to shorter distances of travel; otherwise there would have been more such instances as heavy slope failures are frequent in the Himalayan foothills (major sources of Brahmaputra sediments, Singh and France-Lanord, 2002) due to copious rainfall and recurrent earthquakes (Bora, 2004). While curves 4 and 5 (Figure 5.5) may be attributed to colluvial soil deposits (Zhang and Chen, 2005) resulting from heavy rainfall of June (a monsoon month), ubiquitous sand bars in the river are the likely sources for curves 2 and 3 which represent samples of November and March (both being low rainfall months) respectively. During low flow period, the river flows in multiple channels due to formation of sand bars.

The textural characteristics of the TWLSS and bed sediments are shown in Figures 5.6, 5.7 and 5.8 respectively. Figure 5.6 shows the quantities (% by volume) of different size-class in the TWLSS samples analyzed for particle size, while Figure 5.7 gives the monthly variation of different textural classes (average values of samples taken in the respective months). Silt is the dominant fraction in all the samples and in all the months, with negligible amounts of medium and coarse sands. Bed sediments considered in this study are also dominated by silt (Figure 4.24), indicating the alluvial deposits (which consist mainly of silt and clay) in the Brahmaputra valley as a major source of these sediments. . McLaren (1981) stated that grainsize characteristics of sediments are controlled more by the nature of the source area than by the transportation process or depositional environments.

Singh and France-Lanord (2002) found that the suspended sediments of the Brahmaputra River consisted mostly of silts with clay fractions (< 2 μm) representing 0.5-3% of the total sediments. Coleman (1969) reported that the bed sediments of the Brahmaputra River at Bangladesh consisted of fine sands and silts.

The proportions of various textural classes in the TWLSS and bed sediments were as shown in Table 5.1. The lower values for clay fractions (0.5-3%) in the suspended

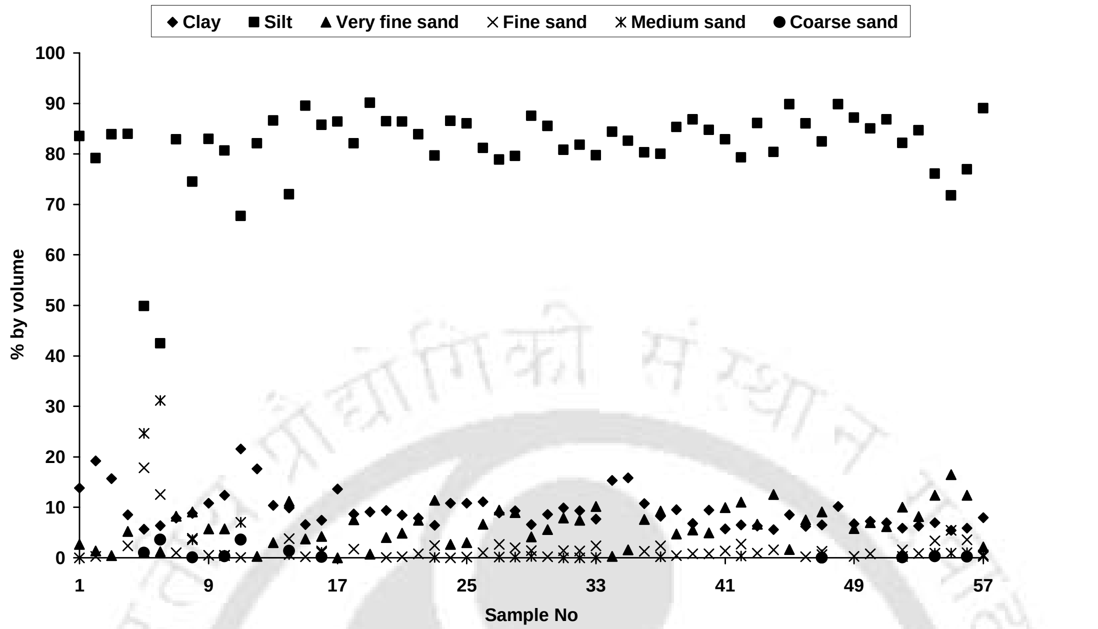


Figure 5.6: Abundance of different textural classes in the Top water layer suspended sediment samples

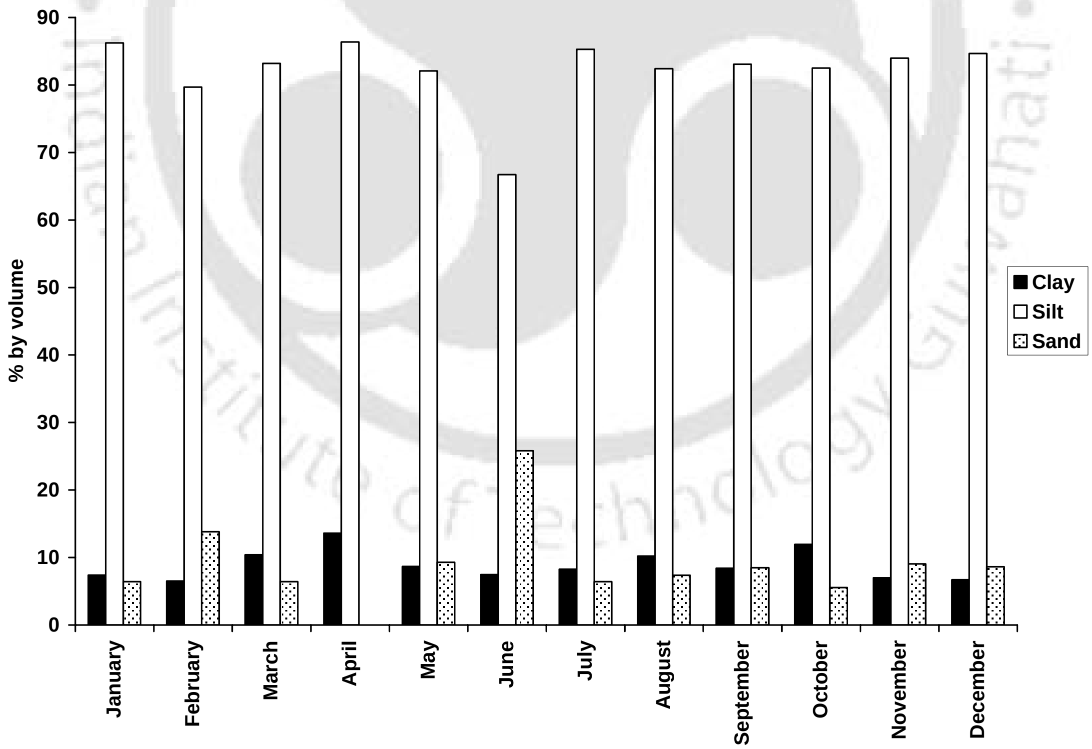


Figure 5.7: Monthly variation of textural properties of Top water layer suspended sediment

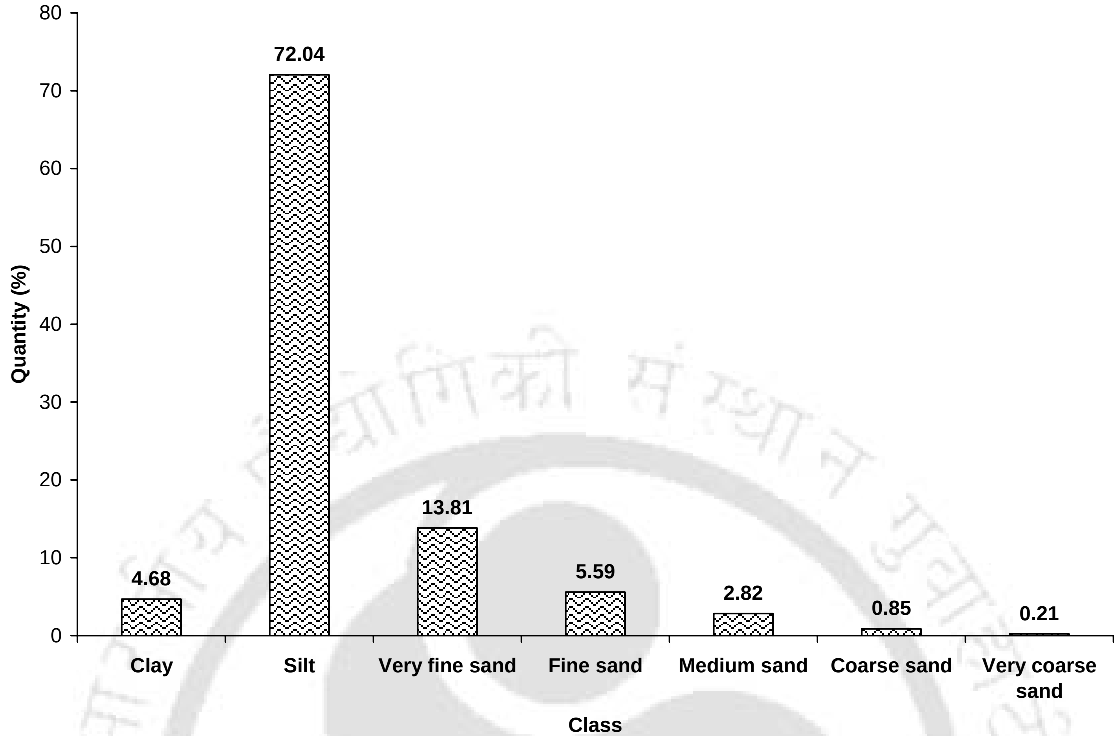


Figure 5.8: Textural properties of bed sediments

sediment of the river, reported by Singh and France-Lanord (2002), may be the result of averaging, as their values were based on samples collected from the Himalayan Front up to Bangladesh.

Table 5.1: Proportions of various textural classes in the sediments

Sediment class	TWLSS	Bed sediment
Clay	6.5-13.6	3.1-4.9
Silt	66.7-86.4	57.3-72.0
Sand	0-25.8	23.3-39.6

Goswami (1985) reported that the clay fraction in the bed sediments of the Brahmaputra River was less than 5% at Pandu, Guwahati, a place very near to the sampling sites of the present study. Although a limited number of bed sediment samples were considered in the present study, the average value (4.68%, Figure 5.8) obtained for clay fractions matches well with the reported value by Goswami (1985), indicating accuracy of sampling procedures in the present study.

The Pie-diagram (Figure 5.9) was drawn with the particle size data (Fine: < 75 µm, Medium: 75-200 µm, Coarse: >200 µm) obtained from CWC on depth-integrated suspended sediment samples collected during the period from December 2003 to October 2008 from the Brahmaputra River at about 100 m downstream of the present study sampling location. Dominance of silt size fractions in the Brahmaputra sediments is revealed from CWC data also. Annual loads of fine, medium and coarse sized sediments are shown in Figure 5.10. A decreasing trend is observed in the total sediment loads for the years shown in this figure. But total sediment load up to 15th October 2008 (309 million tons) is greater than those in 2006 (246 million tons) and 2007 (245 million tons). Analyses of data for more number of years are necessary for recognizing a trend in annual sediment load. Monthly means of discharge and sediment loads of different size fractions in the period from December 2003 to October 2008 are shown in Figure 5.11. The data reveals predominance of fine sediments over the combined loads of coarse and

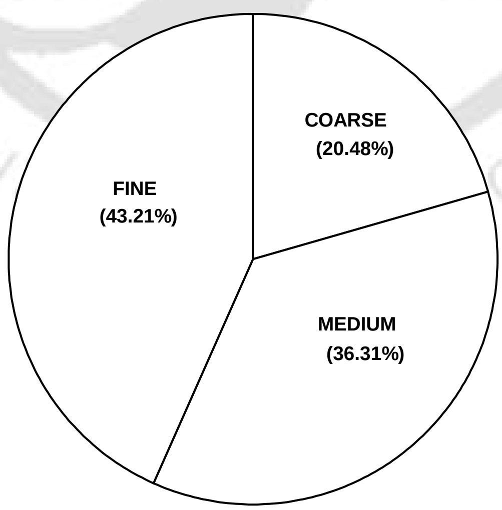


Figure 5.9: Various size-fractions in the Brahmaputra sediments

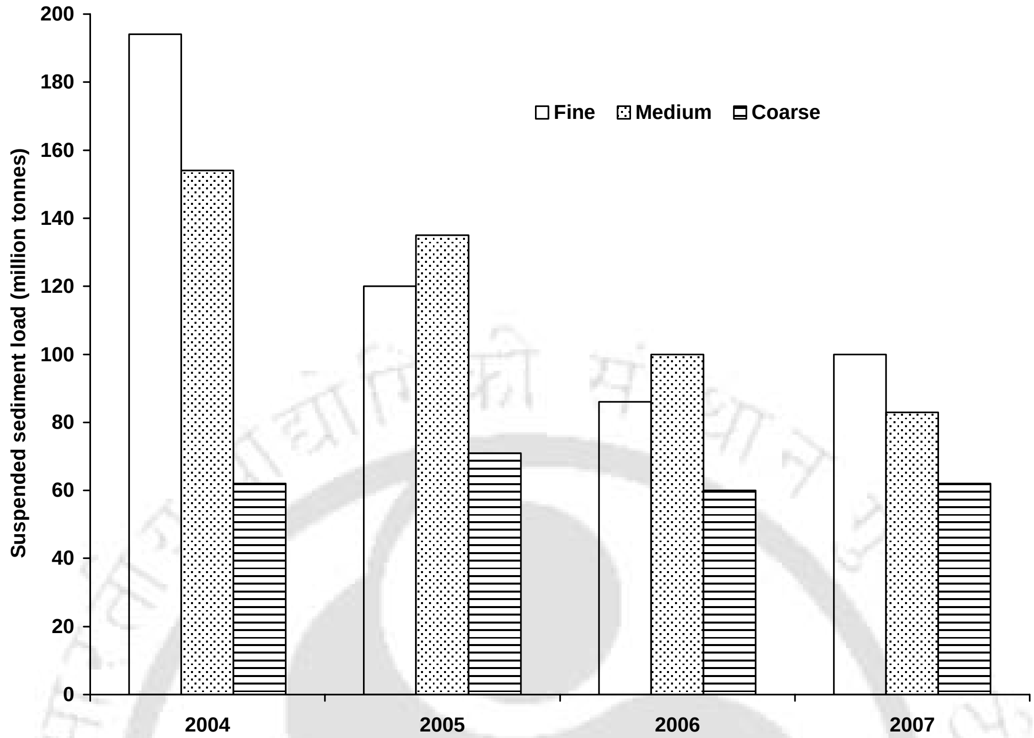


Figure 5.10: Annual loads of fine, medium and coarse size fractions

medium sediments for the period from December to May, and almost equal contributions in the month of November. During monsoon months (June to September), combined load of coarse and medium fractions exceeds fine sediment load as higher turbulence at higher discharges prevents coarser fractions from settling out from the water column (Morris and Fan, 1998). It is interesting to note that the various fractions of the sediments follow similar patterns of increase or decrease as the discharges do. Generally, finer fractions reduce while coarser fractions increase in the suspended sediments, as discharge increases in a river. As silt is the predomonant fraction of the sediments, increase in fine fraction with discharge along with coarse fraction is quite likely. Individual contributions from fine, medium and coarse fractions of sediments to the total load are shown in Figure 5.12. It reveals the dominance of fine sediment over coarse and medium fractions, except in September, when medium size fraction was the highest.

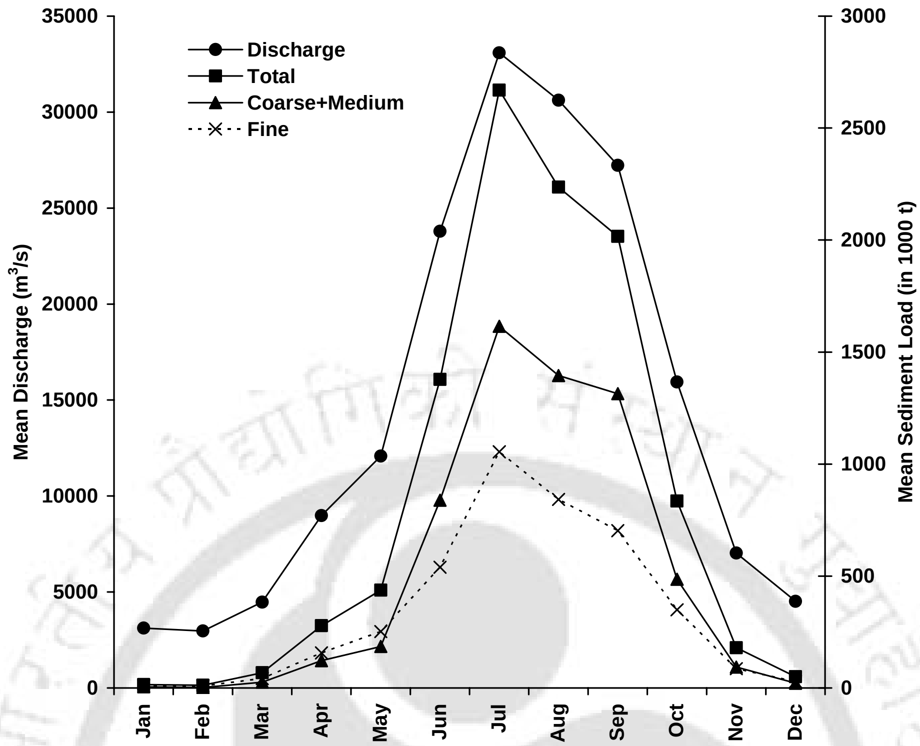


Figure 5.11: Discharge and different size fractions of suspended sediments

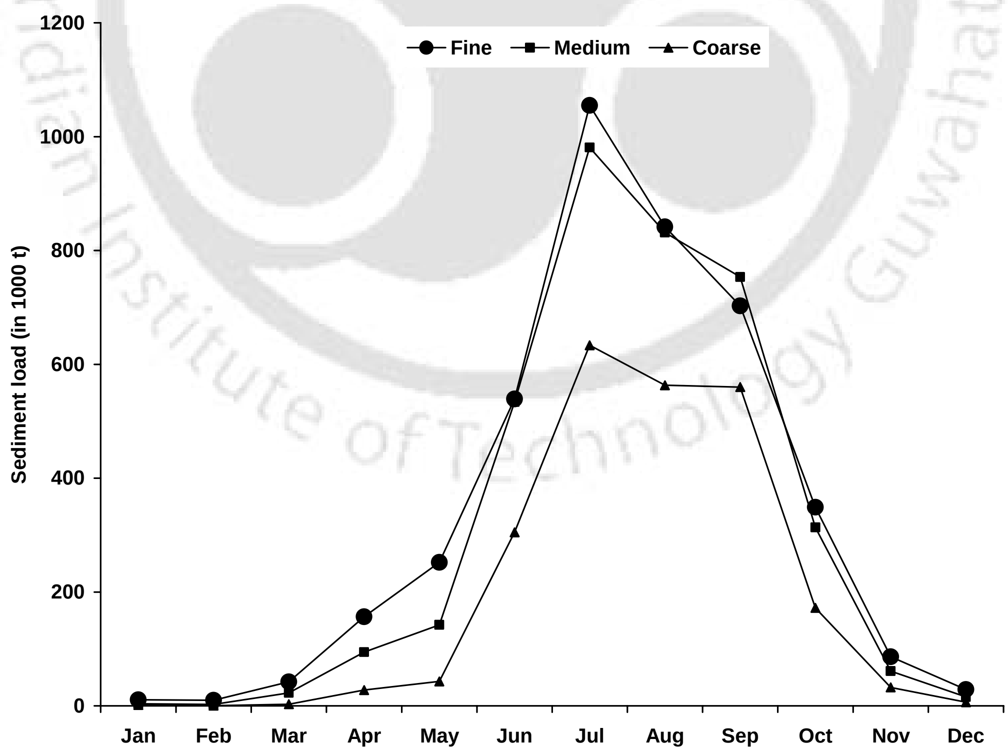


Figure 5.12: Different size fractions in suspended sediments

Datta and Singh (2004) reported coarse, medium and fine fractions of the suspended sediments of the Brahmaputra River at Guwahati as 12.5%, 14.2% and 73.3% respectively. Since the size ranges were not available in the reference cited, the reasons for differences of their values with those of CWC data could not be explained. Dominance of fine fractions in sediments indicates prevalence of chemical weathering in a river basin (Biksham and Subramanian, 1988). Hence, it can be inferred that chemical weathering is dominant in the Brahmaputra basin.

Vaithiyanathan et al. (1988) observed that fine sediments in the Cauvery River were more than the combined loads of coarse and medium sediments from October to July. They stated that fine sediments dominate the sediment load of tropical Indian rivers (e.g., Godavari, Krishna, Cauvery).

Decreased stream power (= VγDS, *V: average velocity in* ms^{-1}, *γ: specific weight of water in* $kg.m^{3}$, *D: average flow depth in m, S: slope of energy gradient* from Goswami, 1985) during low flow period induces deposition of suspended sediment on the river bed. Development of shrinkage cracks in these deposited sediments and the texture reveal dominance of silts in the Brahmaputra River sediments in the study area (Figure 5.13).

Mean grain sizes of the TWLSS ranged from 4.02 to 7.09 φ with an average value of 6.08 φ, and bed sediments from 4.02 to 5.21 φ with an average value of 4.93 φ (Figure 5.14). Hence, both the suspended and bed sediments are predominantly silts (4 to 8 φ). It is seen that the average bed sediments collected during the study are coarser than the suspended sediments by 1.15 φ. Bed sediments of the Ganga River are coarser than suspended sediments by 1.5 φ (Singh et al., 2007). But these results cannot be compared as such because of the differences in nature and numbers of samples in these two different studies. Mean grainsizes for some suspended sediment samples were very unusual [e.g., samples marked outliers (McCormick and Roach, 2008)] and were not considered in Figures 5.14 to 5.18 due to their unusual values

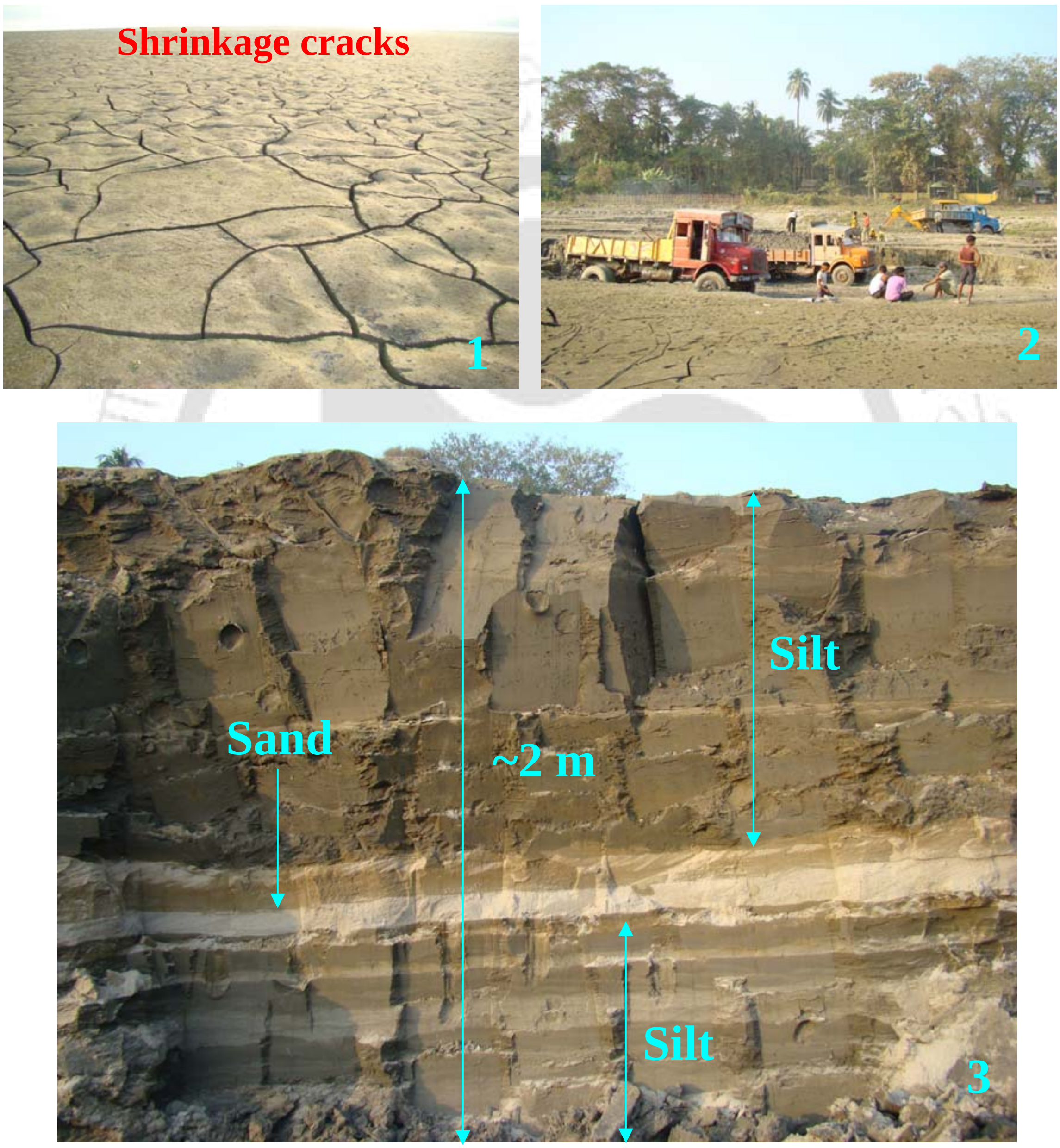


Figure 5.13: Extent and nature of sediment deposition on the Brahmaputra River bed near the sampling sites [1. Huge stretches of sediment deposition; 2. Excavation of deposited sediments; 3. An excavated portion revealing dominance of silts in the sediments]

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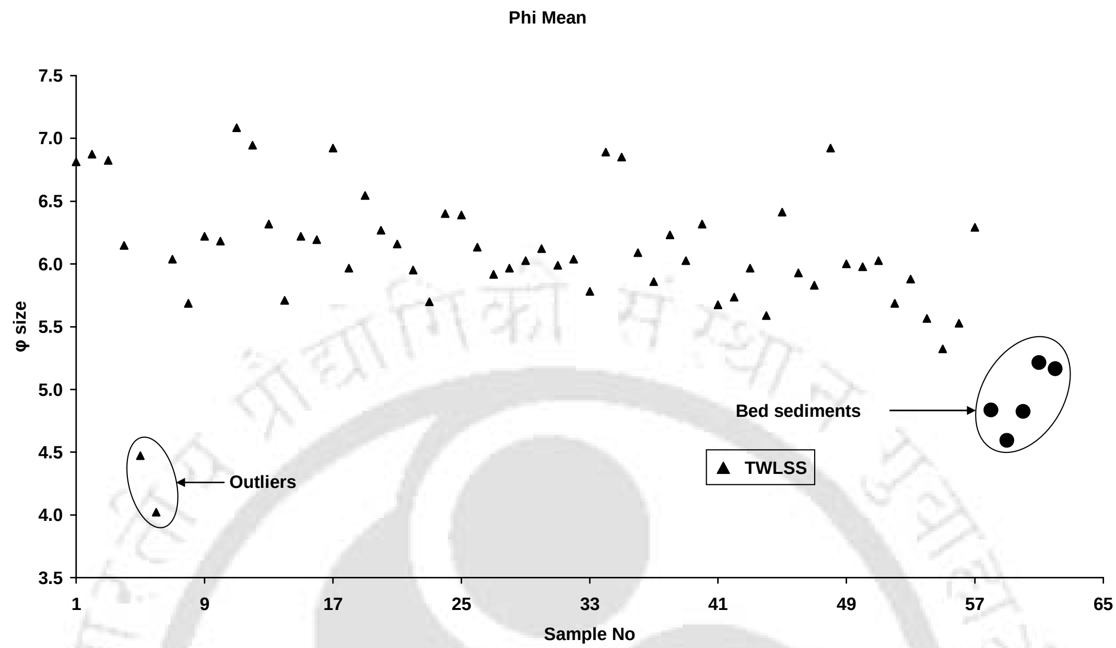


Figure 5.14: Range of sizes in bed sediments and Top water layer suspended sediment

Four factors control standard deviation of river sediment (Singh et al., 2007). They are: (i) the grainsize distribution of the source sediment, (ii) the preferential fluvial entrainment of particles for saltation, (iii) effects of gravity by down slope sediment transportation, and (iv) water flow characteristics. The importance and effect of each control vary temporally and spatially. Values of sorting for suspended sediments ranged from 0.83 (moderately sorted) to 1.80 (poorly sorted) with an average value of 1.37 (poorly sorted). Standard deviation showed a decreasing trend with decrease in the mean grain sizes of suspended sediments. Wren et al. (2000) reported that unlike sands, fine suspended sediments in streams do not show large fluctuations in sizes. Bed sediments were poorly sorted (Figure 5.15). Poor sorting of the sediments may be attributed to dominance of silts (Figures 5.6 and 5.8) in the sediments (Datta and Subramanian, 1997;

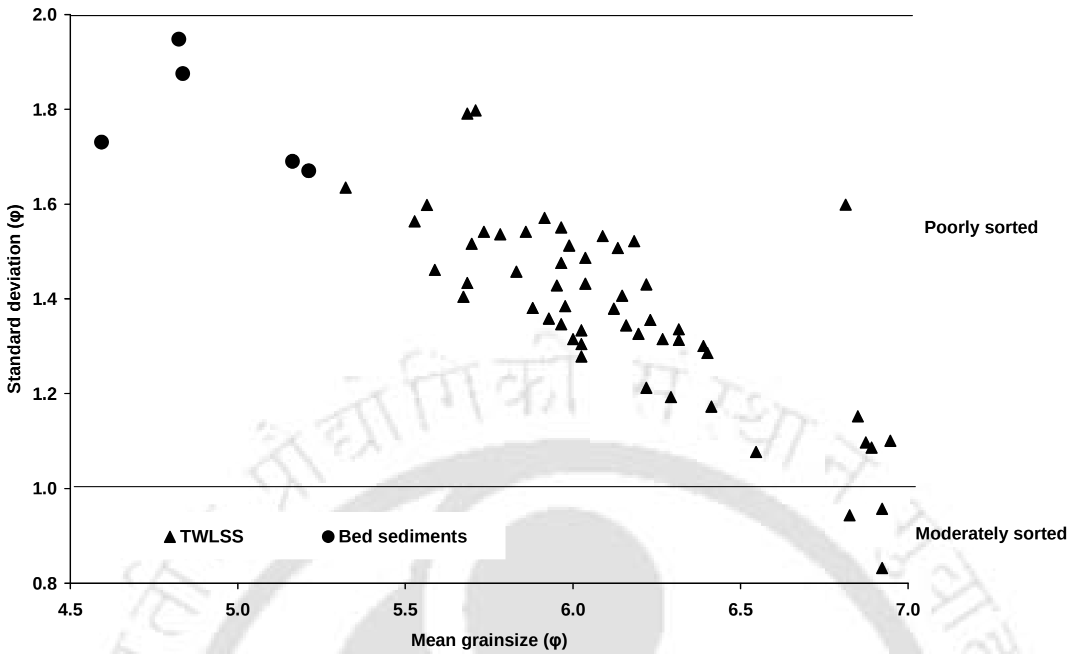


Figure 5.15: Bivariate plot between mean grainsize and standard deviation

Sun et al., 2002). Chakrapani and Subramanian (1994) ascribed poor sorting of the Mahanadi River (India) suspended sediments to supply of comparatively less sorted material from the source. High energy conditions prevailing at the sampling sites and supply of sediments from variable sources (e.g., landslides, slumping of river banks, bed sediment resuspension) may be attributed to the poorly sorted sediments (cited by Pandey et al., 2002 from Collins, 1979 and Hooke, 1989).

Skewness ranged from -0.22 to 0.15 for suspended sediments, -0.10 to 0.11 for bed sediments (Figure 5.16). Overall, size distribution curves were near symmetrical for both bed and suspended sediments. Kurtosis values ranged from 0.64 to 1.11 with an average value of 0.97 for suspended sediments, and for bed sediments the kurtosis values fell in the range 0.99 to 1.09 with an average value of 1.05. The sediments were mostly mesokurtic (Figure 5.17). These results may be attributed to fluctuating hydrodynamic conditions (e.g., shear velocity, vertical component of the current, etc.) in the river and diverse sources of the sediments (Singh et al., 2007; Zhang and Chen, 2005). Skewness and kurtosis of a sediment population are indicators of sorting. Skewness compares sorting in the coarser and finer grained halves of a sediment population, while kurtosis compares sorting in the central portion and the tails of the grain size distribution curves.

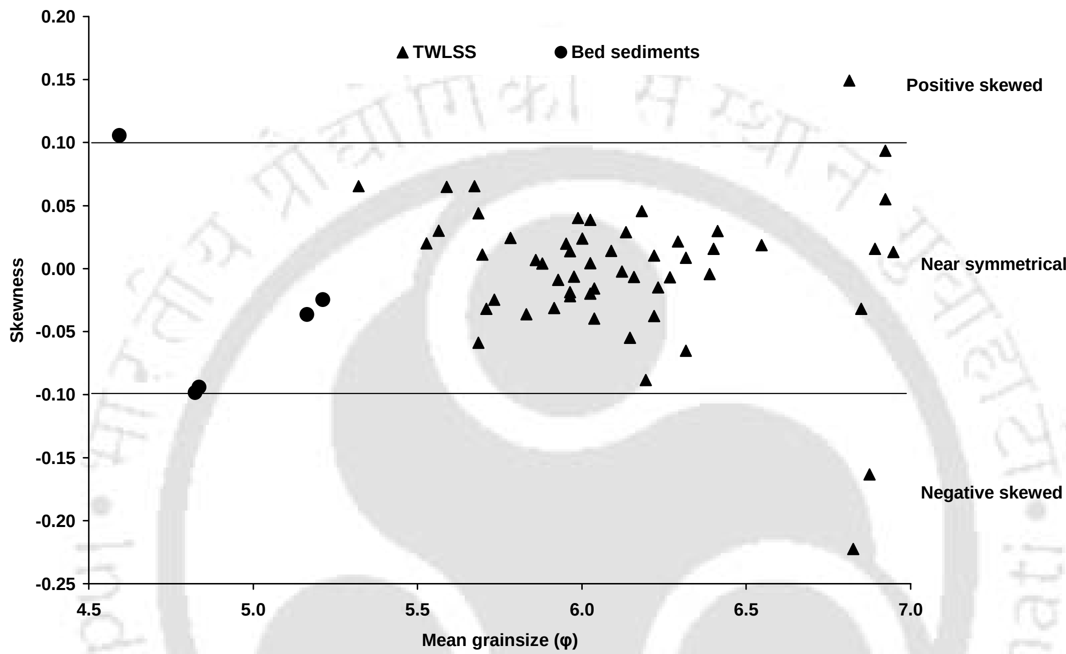


Figure 5.16: Bivariate plot between mean grainsize and skewness

Symmetrical and mesokurtic nature of the grain size distribution curves indicated random distribution of the grain sizes in the sediments considered under the present study.

Singh et al. (2007) reported that the suspended sediment of the Ganga River was moderately sorted, fine to very coarse skewed, and platykurtic to very leptokurtic. They found the bed sediment as very well-sorted to moderately sorted, fine to strongly fine skewed and mesokurtic to very leptokurtic. They observed downstream variations of these parameters and attributed this to the fluctuating energy conditions of the river.

Folk and Ward (1957) showed that a mixing of sediments from two modes resulted in an elliptic or near circular trend in skewness versus a standard deviation diagram (cited by

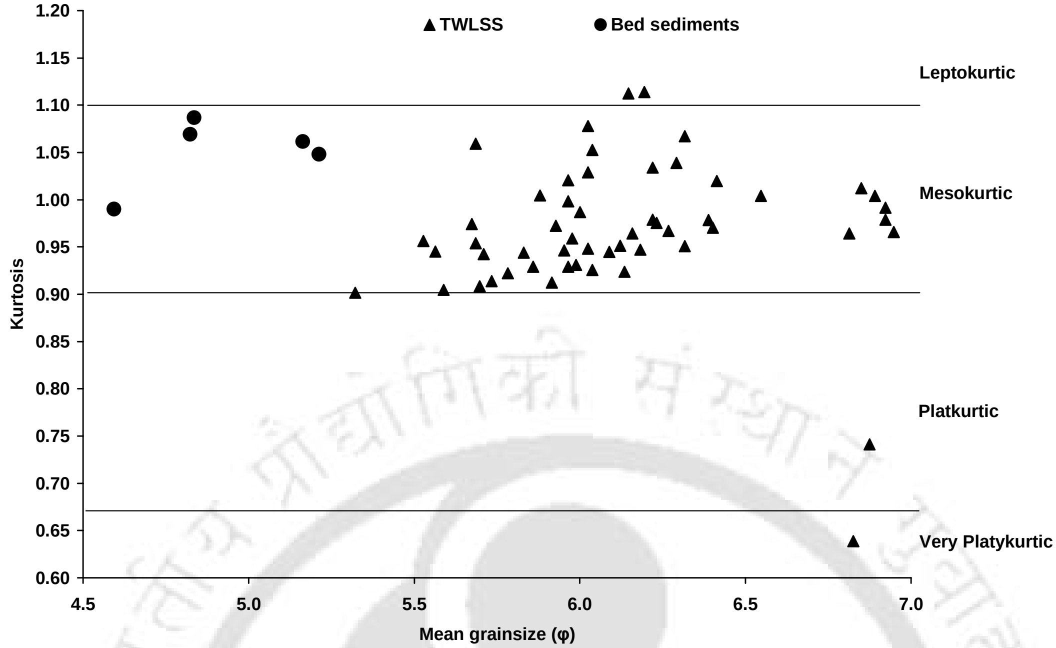


Figure 5.17: Bivariate plot between mean grainsize and kurtosis

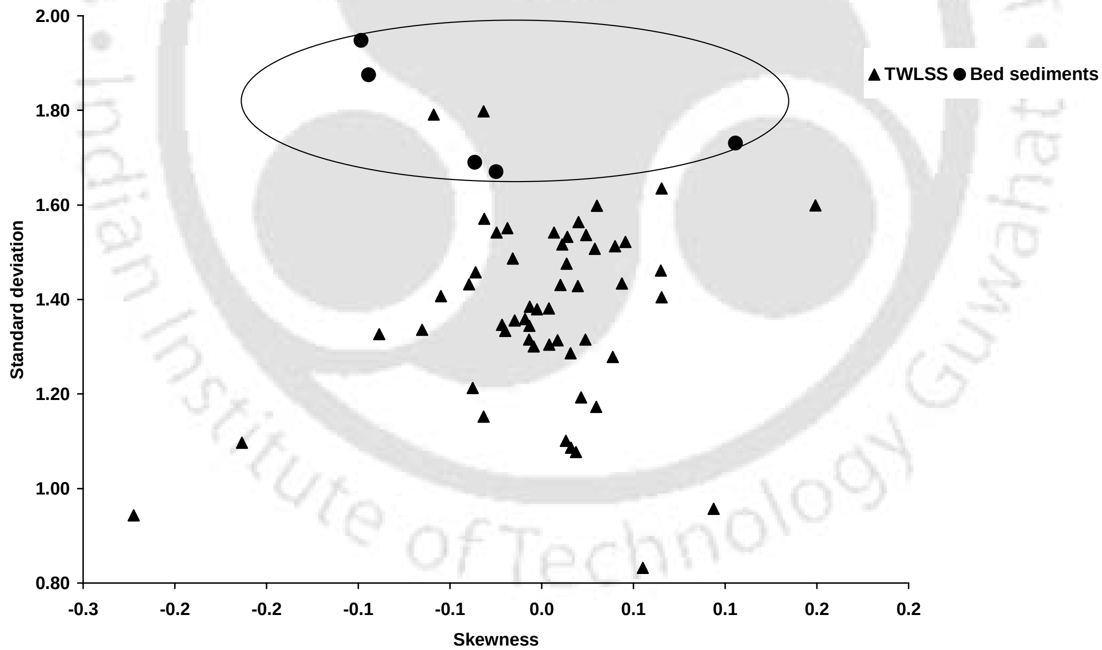


Figure 5.18: Bivariate plot between skewness and standard deviation

Singh et al., 2007). Figure 5.18 showed the plot between skewness and standard deviation. This plot tends to group the suspended and the bed sediments (shown enclosed in an ellipse) in two different areas with only a few samples in between. Similar observations were reported by Singh et al. (2007) for the Ganga River sediments.According to them, these can be used to discriminate sedimentary environments of modern tropical fluvial systems.

Grainsize images help in the interpretation of transport dynamics and are represented by the CM and the FM diagrams. The CM diagram (Figure 5.19) is formed by plotting the coarsest one percentile [C], which represents the competence of the transporting agent (Keulder, 1982), against median diameter of the sediments [M]. Passega and Byramjee (1969) suggested that an M = 100 µm line acts as a dividing line between graded and uniform suspension. Sediments under uniform suspension are generally finer than 250 µm (Singh et al., 2007).

The points in the CM diagram (Figure 5.19) for the samples collected in the present study fall entirely to the left of the M = 100 µm line. It can, therefore, be inferred that both the suspended and the bed sediments in this study belong to the uniform suspension, and do not form a part of the graded suspension (Passega, 1964), indicating absence of a graded suspension in the river at the sampling sites of the present study. This result seems to suggest that bottom turbulence in the river is capable of forming a uniform suspension for the entire length of the water column. Cumulative particle size distribution curves shown in Figure 5.4 also indicated presence of a thick uniform suspension at the sampling site of the present study. Since only limited bed sediment samples could be considered in this study, it is difficult to come to a conclusive inference. Analysis of more bed sediment samples collected at different times of the year will help in better understanding of this aspect. According to Morris and Fan (1998), concentration of fine sediment particles like silt and clays is uniform along a vertical within the water column in most streams due to vertical component of turbulence being greater than the settling rates of these fractions of sediments. As silt is the dominant fraction of the sediments in the Brahmaputra River, this observation of Morris and Fan (1998) supports the existence of a uniform suspension at the sampling sites of the river.

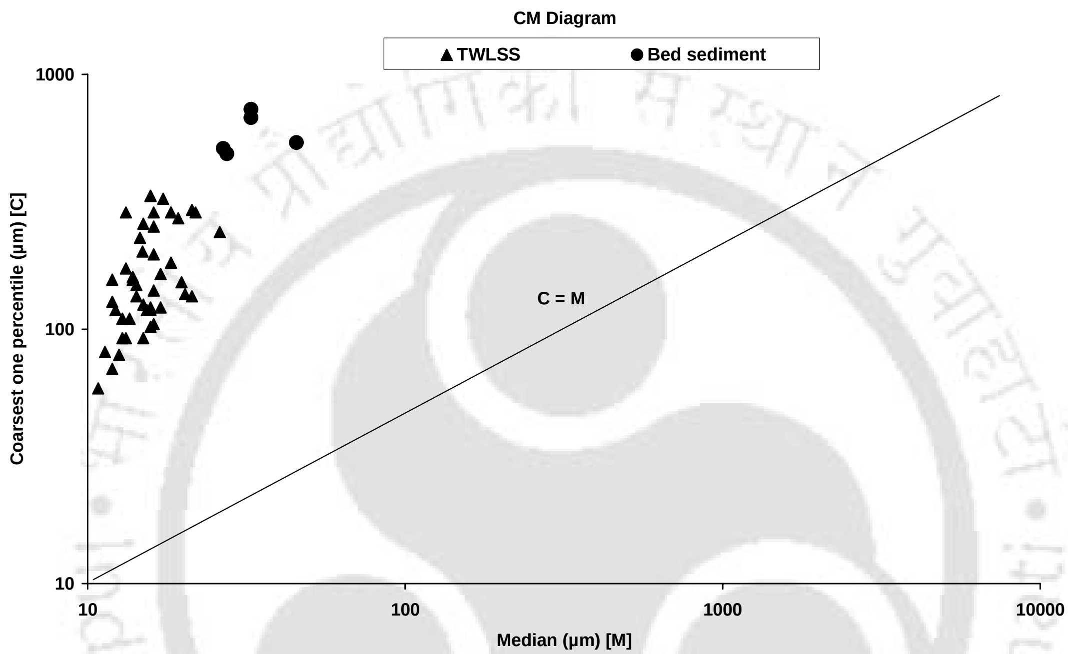


Figure 5.19: Coarsest percentile-Median diagram of Top water layer suspended sediment and bed sediments

The specific surface area (SSA) of the TWLSS was 0.66 ± 0.15 m^2/g (n = 53) with more than 80% of the samples having values less than 0.75 m^2/g. SSA of the TWLSS was found to bear a negative correlation (r = -0.3; p=0.0145) with its concentration (Figure 5.20). A one tail hypothesis test done by using conventional t-test also indicated negative correlation at 95% confidence level (t_{cal} = -2.04; $t_{0.05,\ 51}$ = -1.675). Similar observations were reported by Xu (1999, 2002) for suspended sediments of the Yellow River, China.

At lower concentrations (<120 mg/L), a large scatter was observed with the data-points skewed towards smaller specific surface areas. For concentrations of more than about 320 mg/L, the data-points fell within the 95% confidence range of the linear regression line. Higher concentrations of TWLSS were observed during monsoon months (Figure 4.13) when there was higher turbulence in the river due to increased discharge.

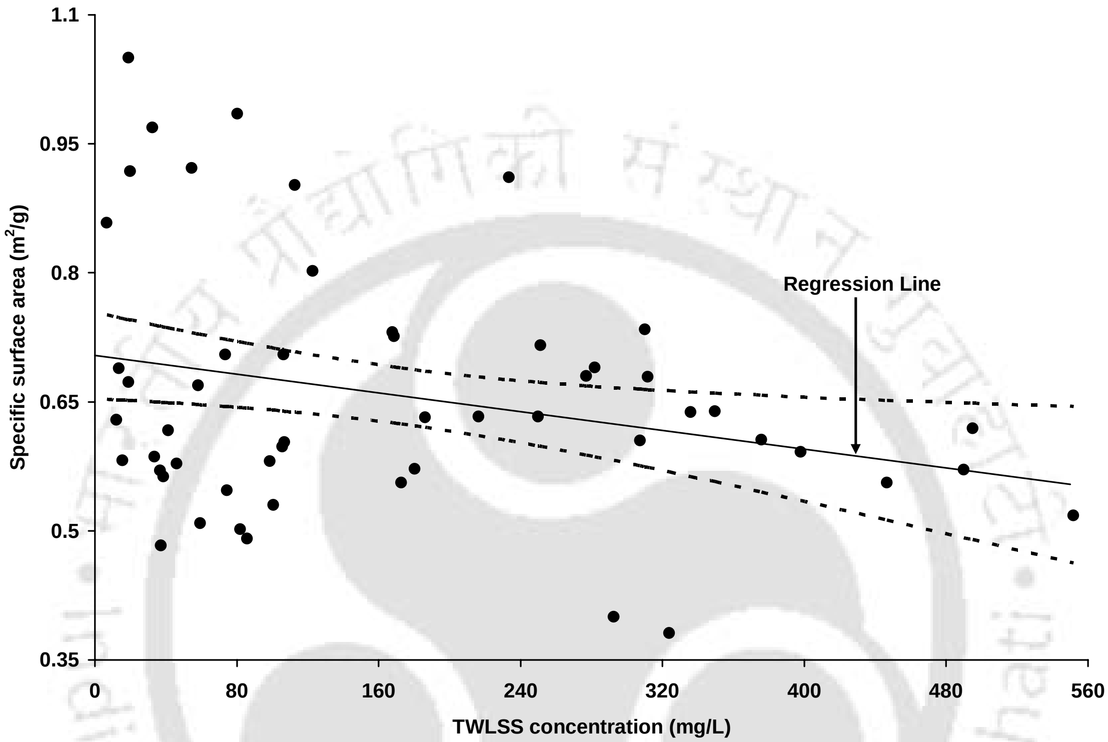


Figure 5.20: Variation of specific surface area with Top water layer suspended sediment Concentration (regression line is bracketed by its 95% confidence range)

Higher turbulence can support bigger-sized sediments in the water column with consequent reduction in SSA, resulting in negative correlation between TWLSS Concentration and SSA. According to Xu (1999), unit weight of liquid phase is much larger than clear water at higher sediment concentrations, leading to substantial decrease in submerged weight of sediment particles which facilitates suspension of coarser grained sediment particles into the water column. This may be another reason for the negative correlation between TWLSS concentration and SSA. The relation between TWLSS concentration and SSA was investigated to explore if more inter-particle collisions at higher TWLSS concentration lead to increased level of finer particles due to abrasion. Since finer particles generally carry more pollutant through adsorption (Horowitz, 1985), increase in finer particles needs to be monitored. Negative correlation between TWLSS concentration and SSA in the present case indicates relatively lesser amounts of finer particles at higher TWLSS concentration.

Different-sized fractions of TWLSS (Figure 5.21) in the sampling site did not show significant variations with discharge, indicating transport of TWLSS to be more supply-controlled than a simple function of flow hydraulics (Walling et al., 2000). In contrast, fractions of different-sized depth integrated suspended sediment (Figure 5.22) varied with discharge at its lower values, but remained unaffected at higher values, indicating their relationship to be controlled by flow hydraulics at lower discharges and by supply at higher discharges (Walling et al., 2000). This dual nature of the suspended

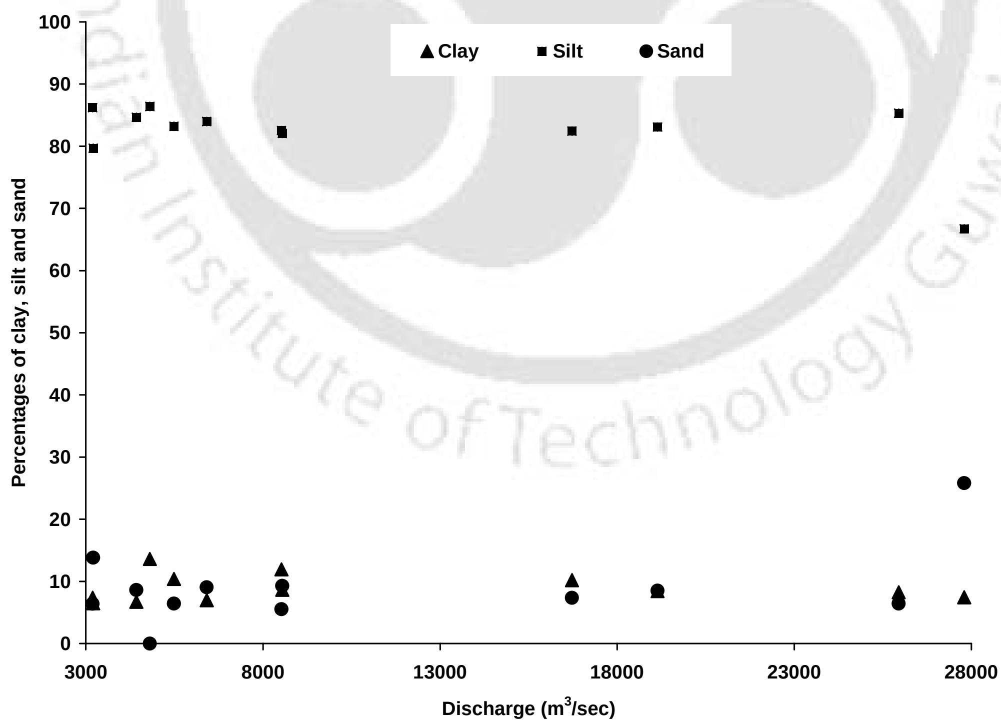


Figure 5.21: Variations of clay, silt and sand fractions of Top water layer suspended sediment with discharge

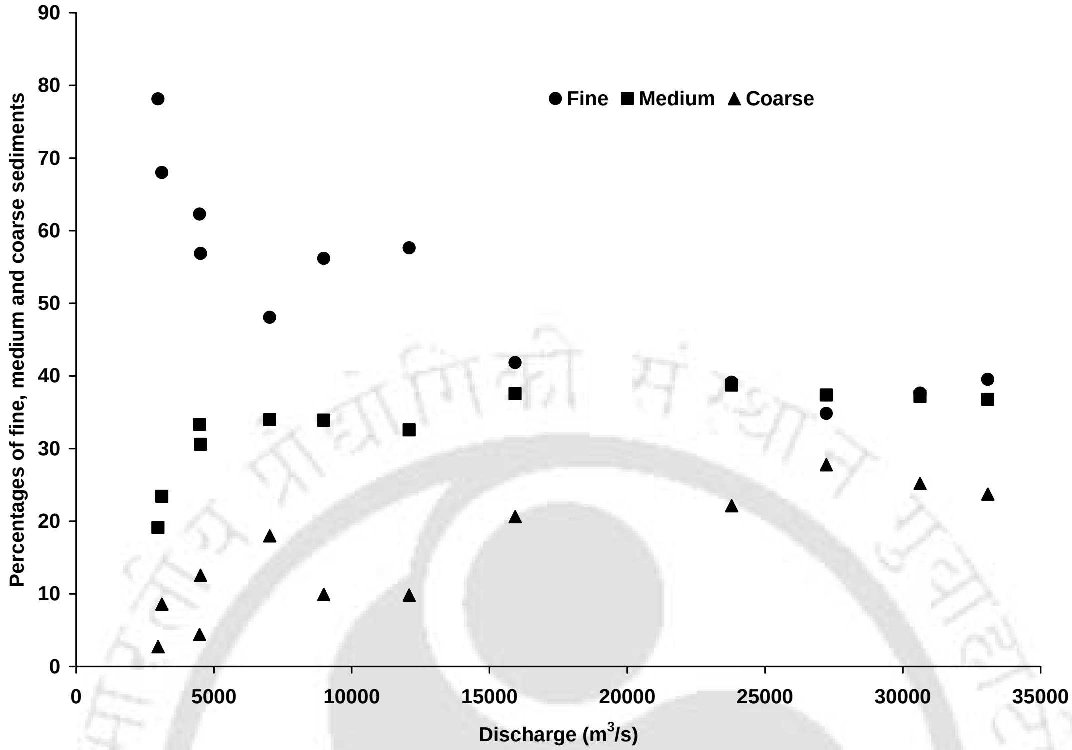


Figure 5.22: Variations of fine, medium and coarse fractions of suspended sediments with discharge

sediments might explain the figure-eight C-Q relationships presented in Figures 4.6 to 4.9: clockwise portion of the loops due to resuspension of deposited sediments in the channel (Datta et al., 1999) by hydrodynamic forces and anticlockwise portion due to supply from the distant sources (Singh and France Lanord, 2002; Tarazon et al., 2009).

The summary of the particle size analyses of the 53 (fifty three) suspended sediment samples carried out in this study is furnished in the following table.

Table 5.2. Summary of particle size analyses of TWLSS

Sl No	Parameter	Mean ± SD
1	Uniformity	0.995 ± 0.186
2	Specific surface area (m^2/g)	0.657 ± 0.146
3	Surface weighted mean diameter (μm)	9.317 ± 1.670
4	Volume weighted mean diameter (μm)	24.121 ± 9.708
5	10% finer than size (μm)	4.198 ± 0.684
6	Median size (μm)	14.402 ± 3.586
7	90% finer than size (μm)	51.723 ± 18.658

5.2. Summary

The top water layer suspended sediment (TWLSS) sizes of the Brahmaputra River were almost normally distributed, but the bed sediment sizes were slightly positively skewed. TWLSS particle sizes were occasionally gap-graded indicating contributions from colluvial soil deposits (e.g., landslide deposits) or from braid bars in the river. TWLSS consisted of mostly 1 to 100 µm sized particles, while bed sediment sizes were in 1 to 1000 µm range. About 82% of the bed sediments fell in the TWLSS size ranges. Silt was the dominant fraction in both TWLSS and bed sediments. Clay contents in TWLSS and bed sediments were found to be 6.5-13.6 % and 4.7 % respectively. Both TWLSS and bed sediments were mesokurtic, normally distributed and poorly sorted. Analyses of cumulative frequency distribution curves and C-M diagram revealed either absence of a graded suspension or presence of a thin layer of it at the present study sampling sites. Specific surface area and TWLSS concentration were found to be negatively correlated.

Average amounts of coarse, medium and fine fractions in the depth-integrated suspended sediment samples were approximately 20.5%, 36.3% and 43.2% respectively. Average load due to fine fractions was more than the combined average loads of coarse and medium fractions during December to May (2003 to 2008). Annual loads (in million tons) of fine, medium and coarse fractions of the suspended sediments were in the ranges 86-194, 83-154 and 60-71 respectively. Dominance of fine fractions in the sediments indicates prevalence of chemical weathering in the basin (Biksham and Subramanian, 1988). The suspended sediment transport was found to be controlled by flow hydraulics at lower discharges and by supply at higher discharges. Since major fraction (more than

80%) of the annual sediment load was found to be transported during the monsoon months which are characterized by higher discharges (Chapter 4), suspended sediment in the Brahmaputra River appears to be mostly supply controlled.

CHAPTER 6

MINERALOGY AND CHEMICAL COMPOSITION OF BRAHMAPUTRA SEDIMENTS

6. Introduction

X-ray diffraction patterns of the sediments were recorded by employing CuK_{α} radiation (λ=0.154056 nm). Minerals were identified with the help of the JCPDS database available with the instrument. Thirty eight bulk samples were analysed, out of which twelve yielded diffractograms with low signal to noise ratio and mineral identification could not be done in those. Semi-quantitative estimation (Schultz, 1964) was employed for mineral quantification.

6.1. Mineralogy

Three of the twenty six diffractograms, where mineral identification was done, are shown in Figures 6.1 to 6.3 and the rest are shown in Appendix-II. Location and time of sample collection are shown in the caption of the figures. Quantities (in percentages) of different minerals in the samples are shown in Figures 6.4 and 6.5. Minerals found in the samples are arranged in descending order of the means (of 25 samples) in Table 6.1.

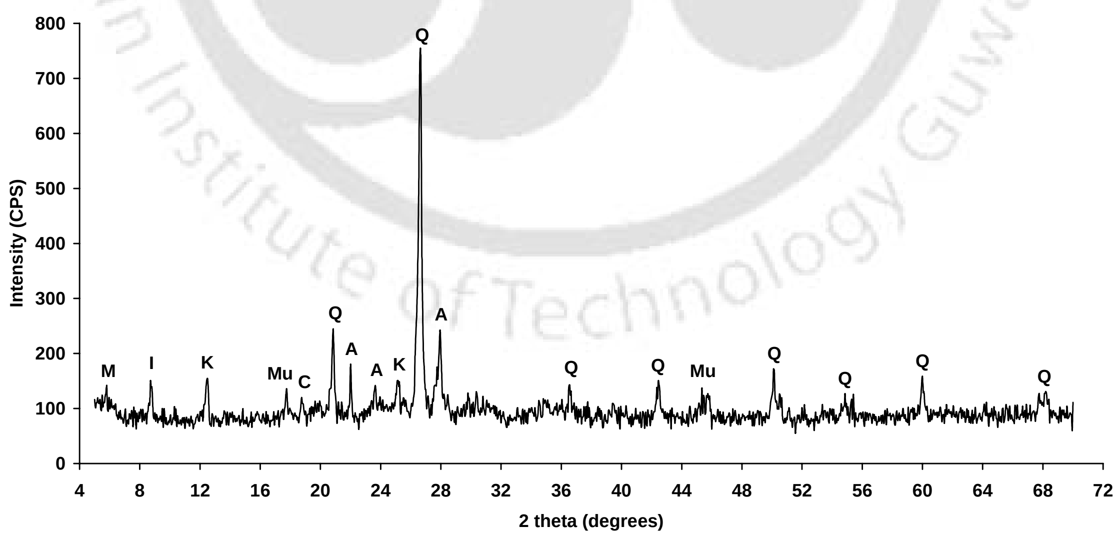


Figure 6.1: X-Ray diffractogram of suspended sediment sample (S4-Feb 2007)

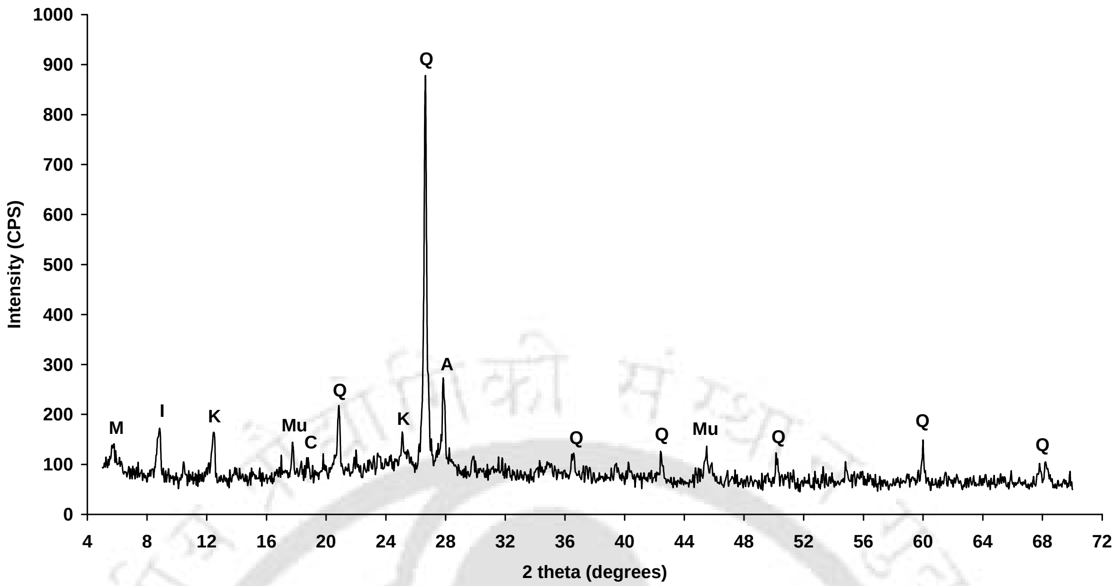


Figure 6.2**:** X-Ray diffractogram of suspended sediment sample (S3-July 2006)

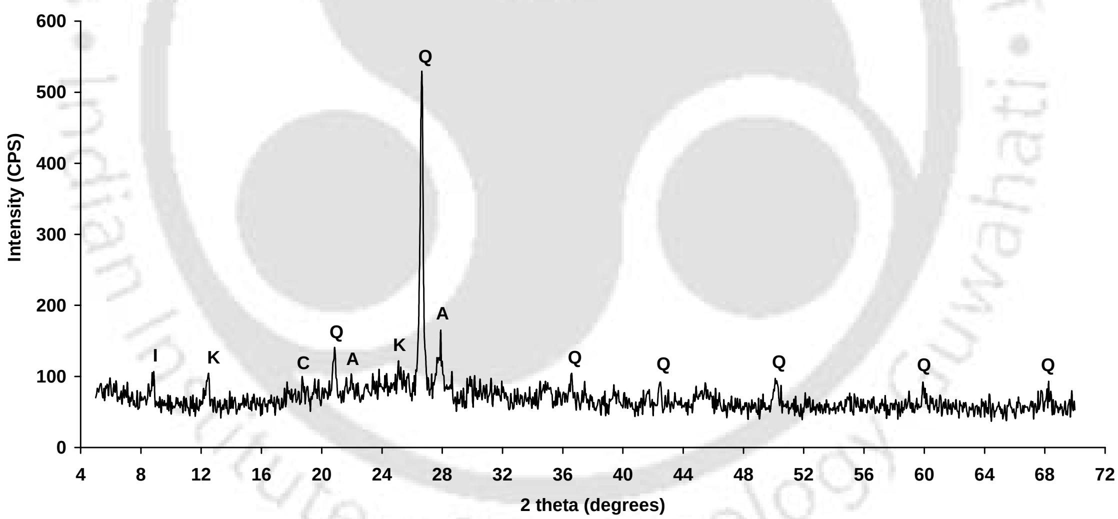


Figure 6.3**:** X-Ray Diffractogram of bed sediment sample (October 2006)

Number of samples (n) in which each mineral was identified is also furnished in Table 6.1. Quartz and illite were present in all the 25 samples while orthoclase was observed in nine samples only. Quartz was the dominant mineral as reported in many other studies (Subramanian, 1979; Singh and France-Lanord, 2002; Mahanta and Subramanian, 2004), which may be ascribed to its resistance to weathering (Rama

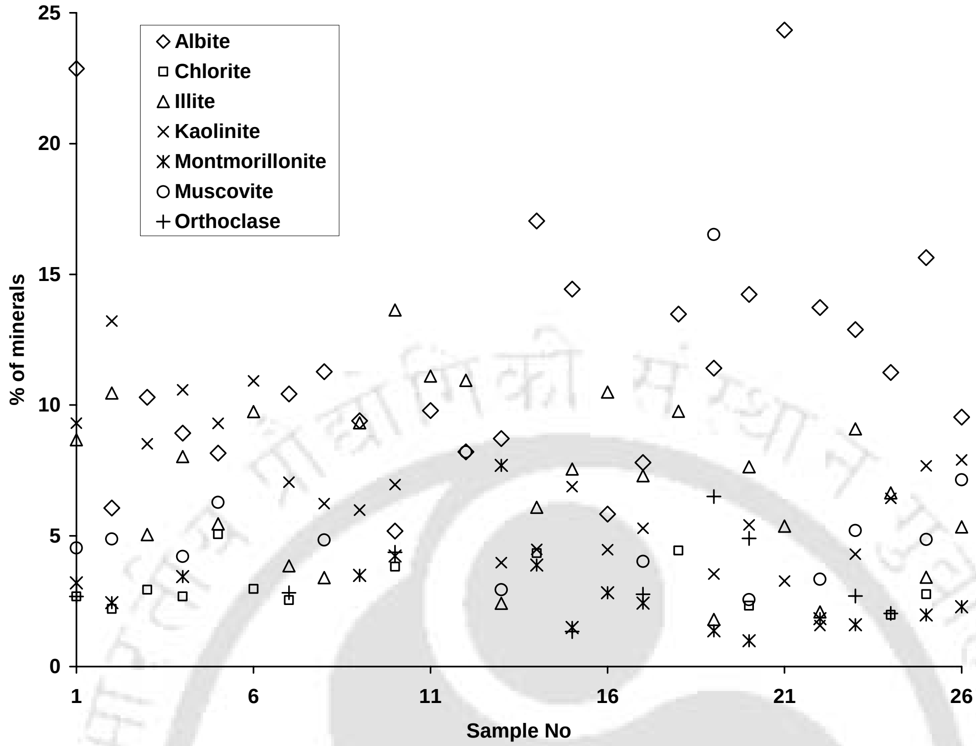


Figure 6.4: Abundances of feldspars, Micas and Clay minerals in the suspended sediment

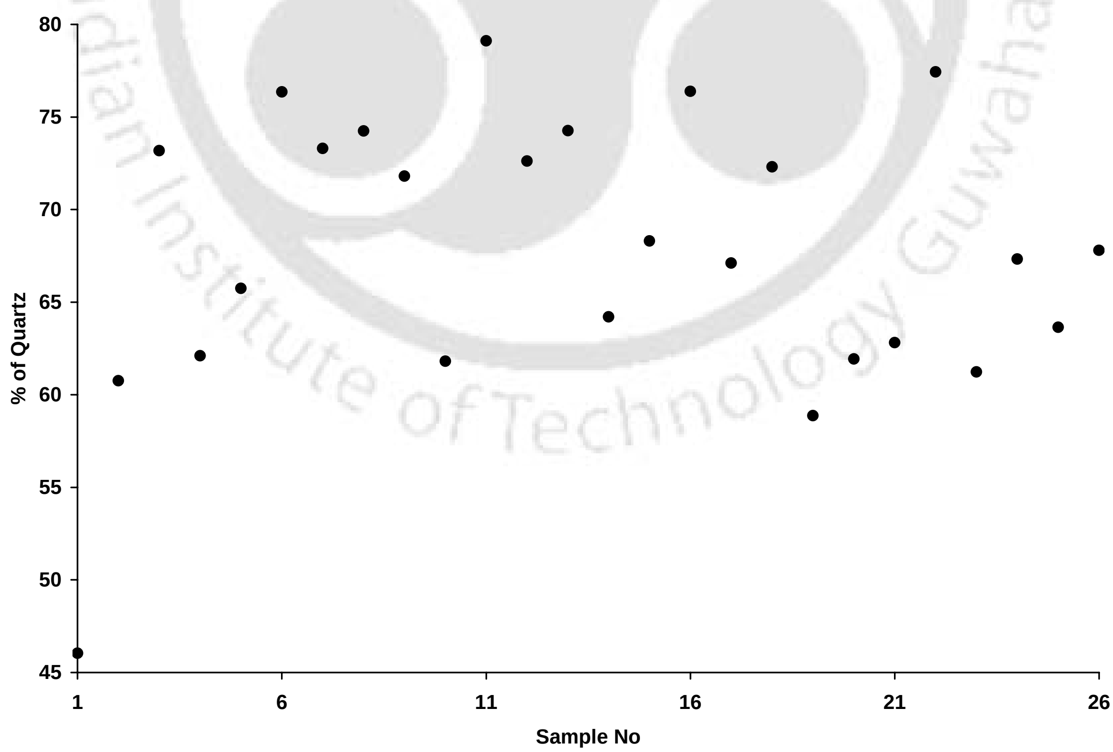


Figure 6.5: Abundances of quartz in the suspended sediment

Murthy and Srivastava, 1979). Illite and kaolinite were found to be as the major clay minerals, which were observed in most of the studies conducted on the Brahmaputra sediments (Subramanian, 1980; Sarin et al., 1989; Mahanta and Subramanian, 2004; Kotoky et al., 2006). Dominance of illite and kaolinite might have resulted from physical weathering of crystalline and metamorphic rocks (Campos et al., 2008) in the Himalayas (Huizing, 1971; Mahanta and Subramanian, 2004).

Monthly variations of minerals are shown in Figures 6.6 and 6.7. The Bed sediment values shown (for comparison) in these plots were averages obtained from the results of analyses of the five samples collected in October 2006.

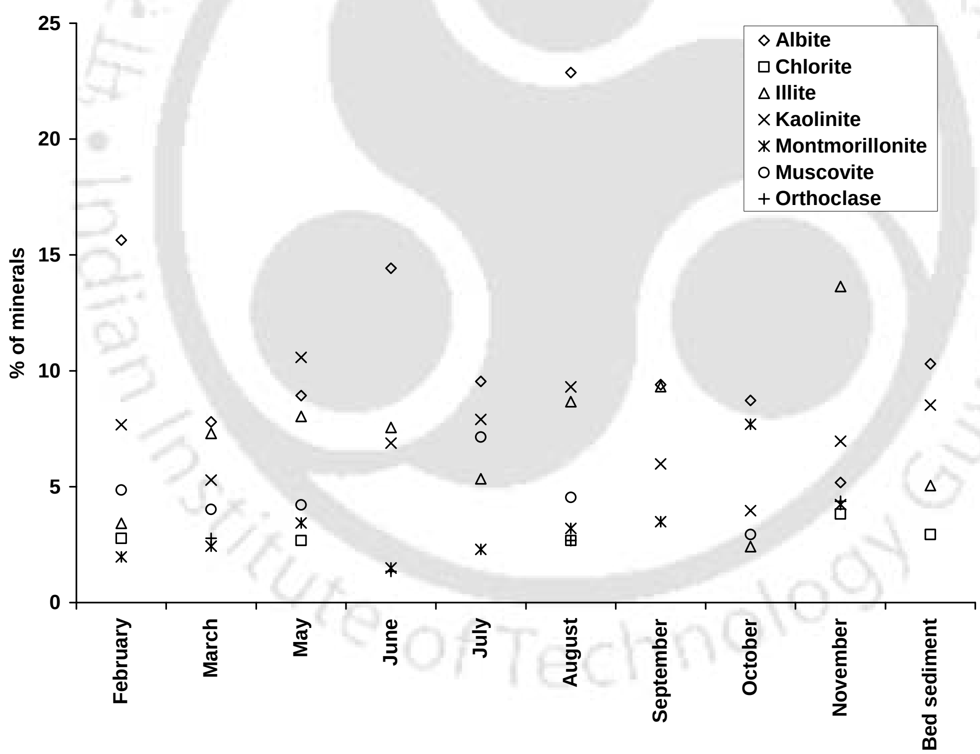


Figure 6.6: Monthly variations of minerals (excluding quartz) in Brahmaputra sediments

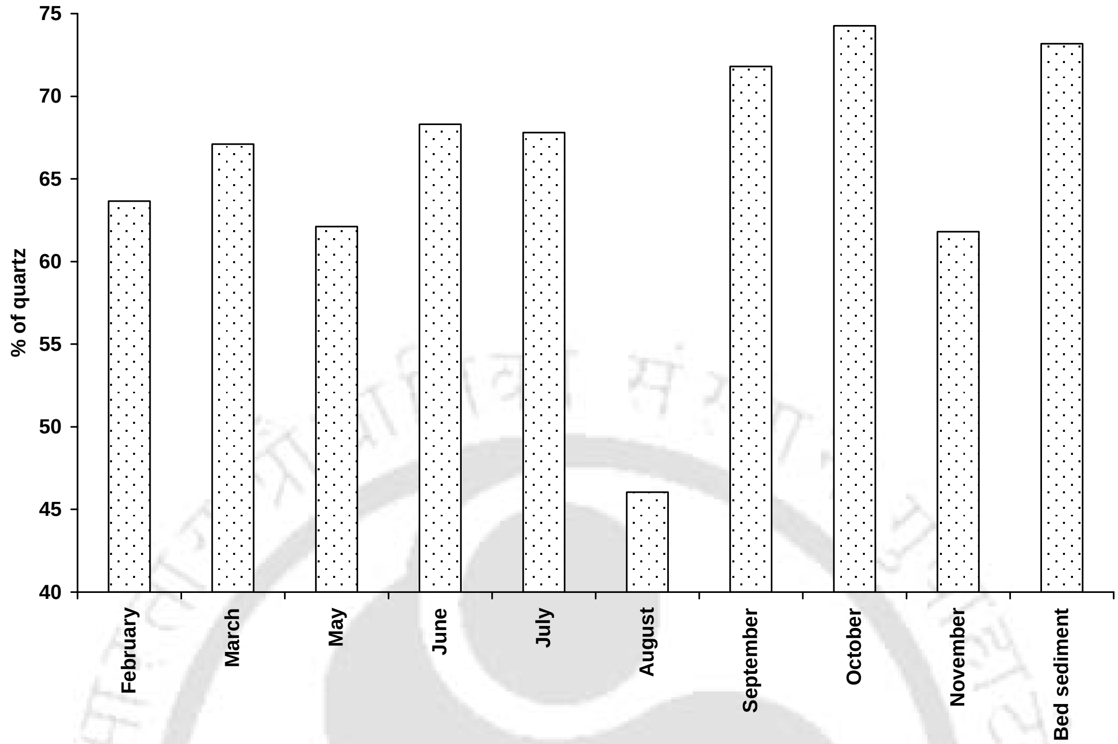


Figure 6.7: Monthly variations of quartz in Brahmaputra sediments

Quantities of minerals in the sediment samples showed high degree of variability, quartz being the exception (Table 6.1). Mineralogical analyses of more samples are necessary for interpretation of some unusual values observed [e.g. quartz (Figure 6.7) and albite (Figure 6.6) in the month of August] in the study. This might be due to contribution from a different population of sediments, differential settlement or alteration of the mineral particles in the upstream of the sampling location (Fayed, 1970; Singh et al., 2005; Guyot et al., 2007). According to Warren and Zimmerman (1994), fluvial systems are inherently variable and such outlier points are not unusual.

Chlorite, illite and kaolinite formed more than 85% of the total clay minerals (Table 6.1). Detrital contribution in the form of quartz, feldspar and mica constituted more than 80% in both the suspended and the bed sediments (Table 6.2). Similar observations were reported by Mahanta and Subramanian (2004) for the Brahmaputra

River sediments. They ascribed the abundance of the silicate minerals to extensive weathering of granite, gneiss and sandstone terrains in the basin having wet humid climate.

About 62% of the samples showed presence of montmorillonite (Table 6.1), which are generally attributed to the volcanic rocks present in the upper drainage basin of the Brahmaputra River (Sarin et al., 1989; Hu Ming-Hui et al., 1982 [Cited by Mahanta and Subramanian, 2004]). In an alkaline environment (pH of Brahmaputra River is 7.6 ± 0.2, Mahanta and Subramanian, 2004; >8 by Mandal, 2005; 8.33±0.50 by Hanumagutti, 2006) containing silica and aluminium, montmorillonite may be formed from aluminosilicates in the presence of magnesium or ferric and ferrous ions (Fayed, 1970; Singh et al., 2005). Sedimentary rocks might also act as sources for smectites [cited from (Rao et al., 1988; Kolla and Rao, 1990; Segall and Kuehl, 1992; Wijayananda and Cronan, 1994] by Datta and Subramanian, 1997; cited from France-Lanord et al., 1993 by Heroy et al., 2003]. According to Campos et al. (2008), montmorillonite is formed through chemical weathering and its quantity increases when sediment sources contain volcanic rocks (Campos et al., 2008). Presence of montmorillonite was reported in the suspended sediments of the Brahmaputra River in some other studies also (Mahanta and Subramanian, 2004; Saxena, 2006). These results indicate prevalence of chemical weathering in the Brahmaputra basin.

Among the feldspars, albite was the highest in concentration (Table 6.1). Abundance of albite in the basin and/or alkaline condition in the river are likely to be the reasons for high amounts of this mineral in the sediments (Singh et al., 2005). Many authors have reported feldspars, although not specifically as albite, as dominant minerals in the Brahmaputra River sediments (Huizing, 1971; Subramanian, 1979; Datta and Subramanian, 1997; Singh and France-Lanord, 2002). Presence of albite in the Brahmaputra River sediments was reported by some other authors also (Kotoky et al., 2006; Saxena, 2006).

Mineralogical compositions of bed sediments (sampled in the months of October) did not show significant variation with October samples of TWLSS. Since mineralogy is particle size dependent (Eby, 2004) and there is a likelihood of uniform suspension extending up to the bed of the Brahmaputra River (Chapter 5), similarities in mineralogical characteristics between bed sediments and TWLSS is expected. Due to limited number of bed sediment samples considered in this study, drawing any inferences in this regard is likely to be erroneous.

Both IC (Illite-Chlorite) and SK (Smectites-Kaolinite) mineral associations were found to be equally dominant for Brahmaputra sediments (Figure 6.4). According to some studies (Brass and Raman, 1990; Debrabant et al., 1993; Derry and France-Lanord, 1996), IC is associated with high sediment fluxes and periods of physical weathering and Himalayan uplift, while SK is associated with periods of chemical weathering and tectonic relaxation. So, both physical and chemical weathering are likely to be dominant in the Brahmaputra basin.

Table 6.1: Suspended sediment (bulk) mineralogy of the Brahmaputra River

Parameters	Q	A	I	K	Mu	O	C	M
n	25	24	25	22	14	9	12	16
Mean	67.50	11.69	7.19	6.58	5.68	3.35	3.15	2.82
SD	7.49	4.81	3.20	2.82	3.48	1.61	1.01	1.61
COV	11.10	41.13	44.56	42.83	61.28	48.01	31.90	56.98

[Abbreviations/symbols in the Table: Q = Quartz, A = Albite, I = Illite, K = Kaolinite, Mu = Muscovite, O = Orthoclase, C = Chlorite, M = Montmorillonite, n = A mineral was detected in "n" samples out of 25 analyzed, SD = Standard deviation, COV = Coefficient of variation]

An idea of the chemical and physical weathering processes operating in a basin can be obtained from the quartz : feldspar (Q:F) and quartz : mica (Q:M) ratios. Although

Table 6.2: Quartz : Feldspar and Quartz : Mica ratios in Brahmaputra sediments [Q = Quartz. F = Feldspars, M = Micas]

Sl No	Sample	Q	F	M	Clays	Q:F	Q:M
1	S1-Oct 2004	73.30	13.25		13.44	5.53	
2	S3-Oct 2004	74.26	8.72	2.94	14.08	8.52	25.26
3	S5-Oct 2004	74.24	11.28	4.84	9.63	6.58	15.34
4	S1-May 2005	72.31	13.48		14.20	5.36	
5	S3-May 2005	62.11	8.93	4.21	24.73	6.96	14.75
6	S4-May 2005	64.20	17.04		18.79	3.77	
7	S3-Jun 2005	65.74	8.16	6.28	19.82	8.06	10.47
8	S4-Jun 2005	68.30	15.77		15.92	4.33	
9	S3-Sep 2005	76.38	5.83		17.79	13.10	
10	S4-Sep 2005	71.81	9.40		18.79	7.64	
11	S3-Nov 2005	61.81	9.55		28.65	6.47	
12	S3-Mar 2006	67.11	10.57	4.02	15.02	6.35	16.69
13	S3-May 2006	79.11	9.79		11.11	8.08	
14	S3-Jul 2006	67.80	9.54	7.14	15.53	7.11	9.50
15	S4-Jul 2006	72.62	8.21	8.21	10.95	8.85	8.85
16	S3-Aug 2006	46.04	25.55	4.54	23.86	1.80	10.14
17	S4-Aug 2006	58.87	17.91	16.52	6.71	3.29	3.56
18	S3-Sep 2006	60.75	6.06	4.88	28.31	10.02	12.45
19	S4-Sep 2006	61.93	19.13	2.56	16.38	3.24	24.19
20	S3-Oct 2006	76.35			23.64		
21	S4-Oct 2006	62.82	24.34		8.64	2.58	
22	S3-Nov 2006	77.43	13.73	3.34	5.49	5.64	23.18
23	S4-Nov 2006	61.23	15.59	5.20	14.99	3.93	11.78
24	S3-Feb 2007	67.33	13.28		15.05	5.07	
25	S4-Feb 2007	63.65	15.64	4.86	15.84	4.07	13.10
26	Bed sediment	73.18	10.30		16.51	7.10	
Average		67.72	12.84	5.68	16.30	6.14	14.23
SD		7.42	5.12	3.48	5.99	2.56	6.29
COV		10.96	39.89	61.28	36.74	41.75	44.23

both quartz and feldspar are products of mechanical breakdown of drainage basin rocks of the catchment area, feldspar is highly susceptible to chemical weathering and gives rise to clay minerals. Values of Q:F and Q:M ratios in average sediments are 2.3 and 2.2 respectively (Gupta and Subramanian, 1994). Higher values of Q:F (6.14±2.56) and Q:M

(14.23±6.29) (Table 6.2) in the Brahmaputra sediments indicates loss of feldspar and mica due to chemical weathering (Pandey et al, 2002). Low mica content may also be attributed to the geochemical environments and/or bedrock geology of the Brahmaputra basin (Gupta and Subramanian, 1994; Heroy et al., 2003)

6.2. Morphology and sediment composition

The shapes of sediment particles and the microscopic textural patterns on their surfaces provide information about the physical and chemical processes to which the particles have been subjected (Pandey et al., 2002).

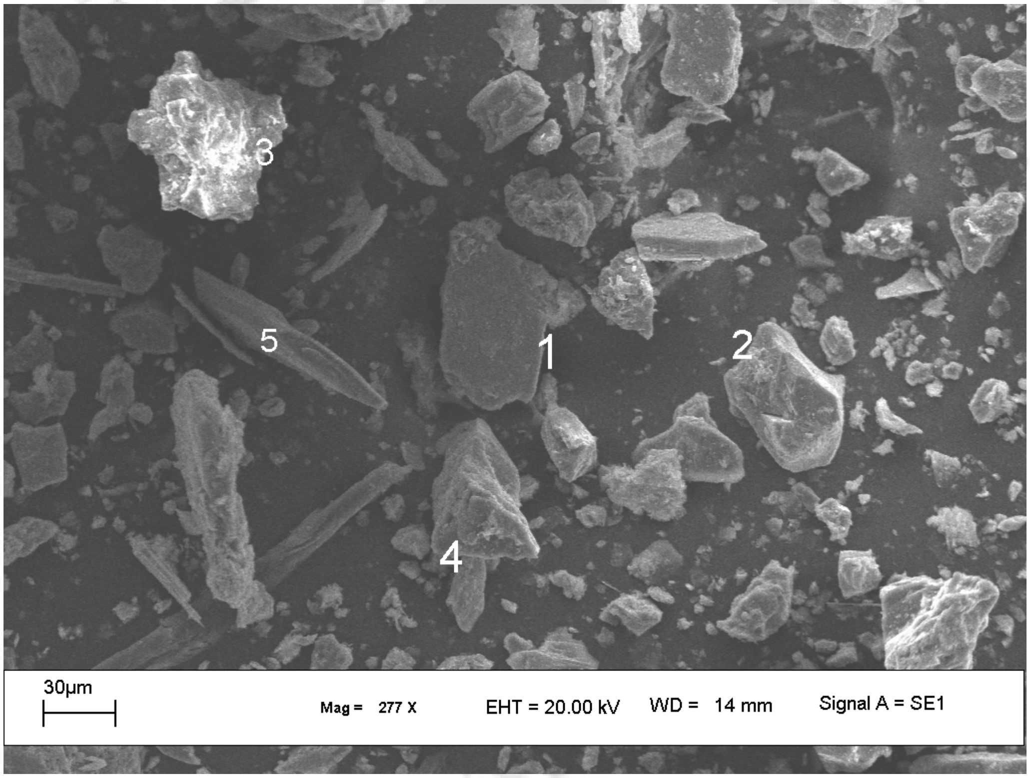


Figure 6.8A: SEM image of suspended sediment (S4-Feb 2007) **{1.** Al-Si-K-Ti-Fe-Cu **2.** O-Si [**Q**] **3.** O-Mg-Al-Si-Fe [**C**] **3.** O-Al-Si-Fe [**C**] **4 & 5.** O-Al-Si-Ca-Fe [**M**]**}**

Scanning electron micrographs (Figures 6.8 A, 6.8 B, 6.9 and 6.10; rest in Appendix-III) revealed that the shapes of the sediment particles were oblate, prolate or bladed. Equant shaped particles were almost absent. The particles had sharp edges, reflecting their textural immaturity. Surface textures also revealed angular outlines, fractured blocks, conchoidal breakage, parallel and sub-parallel steps and even surfaces. Dissolution pits and hollows, secondary growth and surface etching visible on the sediment particles can be attributed to the chemical activities undergone by them (Pandey et al., 2002).

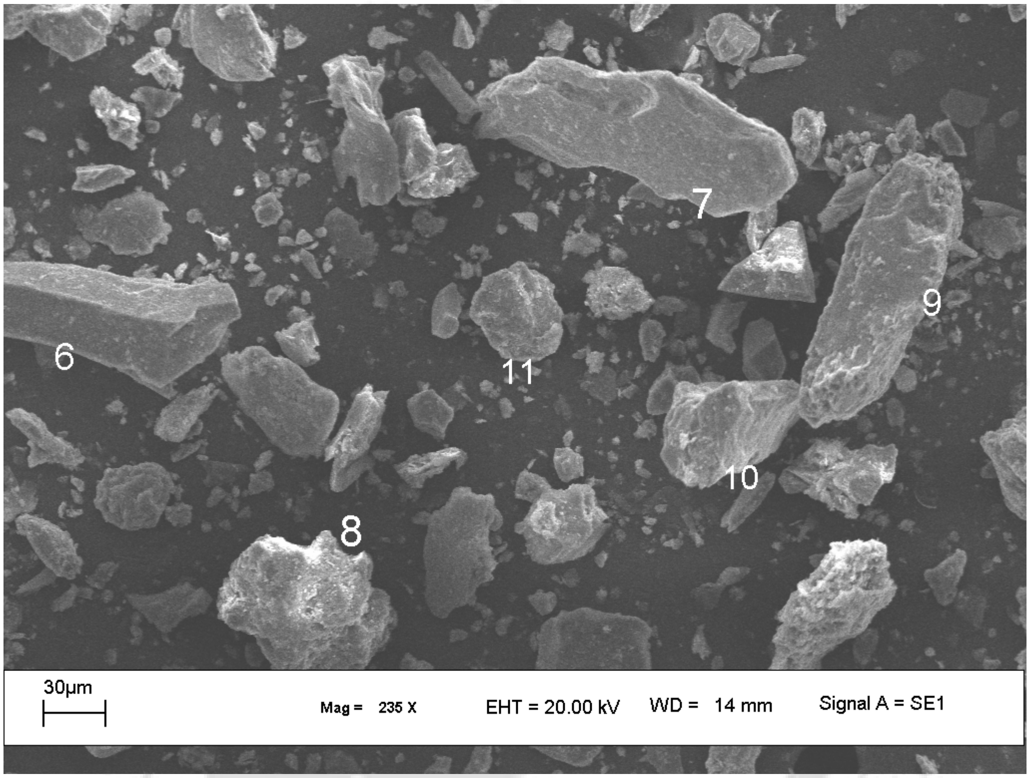


Figure 6.8B: SEM image of suspended sediment (S4-Feb 2007) **{6 & 9.** O-Si [**Q**] **7.** O-Mg-Al-Si-Fe [**C**] **8 & 11.** O-Al-Si [**K**] **10.** O-Al-Si-K-Fe [**I**]**}**

Suspended sediments of the Brahmaputra River were found to be mostly supply controlled in the present study (Chapter 5), and Singh and France Lanord (2002) reported the Siang-Tsangpo Rivers as major sources of these. Moreover, particle sizes of the sediment were usually less than 1000 µm (Chapter 5). The textural immaturity of the suspended sediments at the sampling sites, even after hundreds of kilometers' of

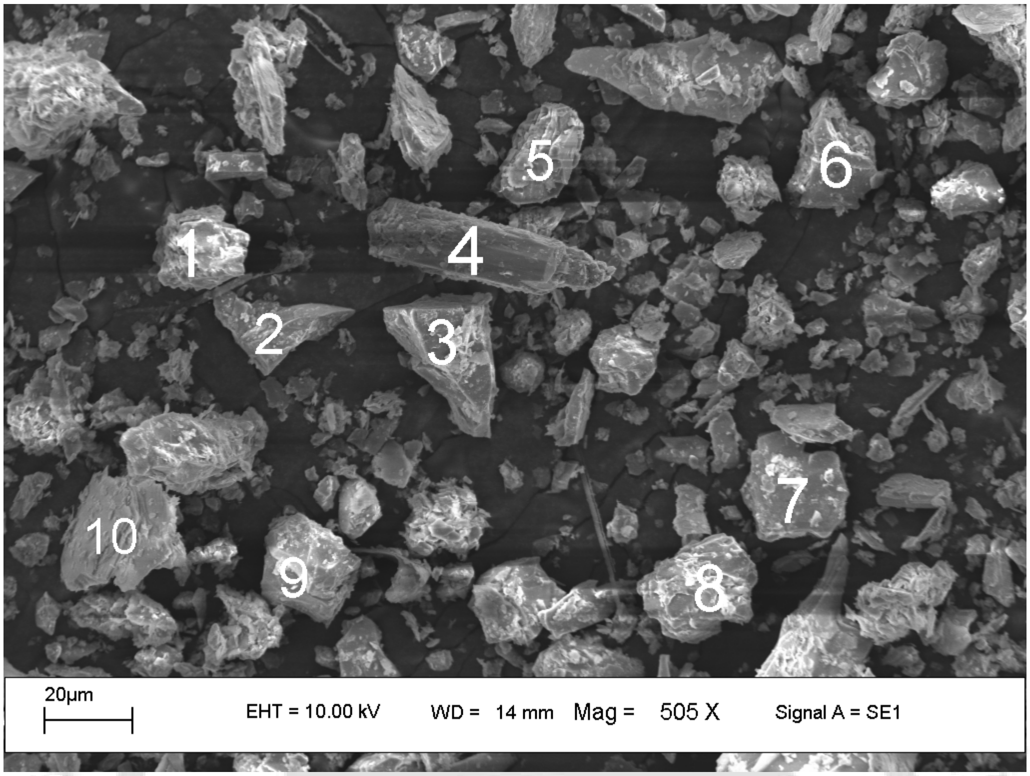


Figure 6.9: SEM image of suspended sediment (S3-Jul 2006) **{1 & 10.** O-Al-Si-K [**Mu**] **2, 6 & 8.** O-Si [**Q**] **3.** O-Al-Si [**K**] **4.** O-Mg-Al-Si [**C**] **5.** O-Na-Al-Si [**A**] **7.** O-Mg-Al-Si-Fe [**C**] **9.** O-Al-Si-Ca [**M**]**}**

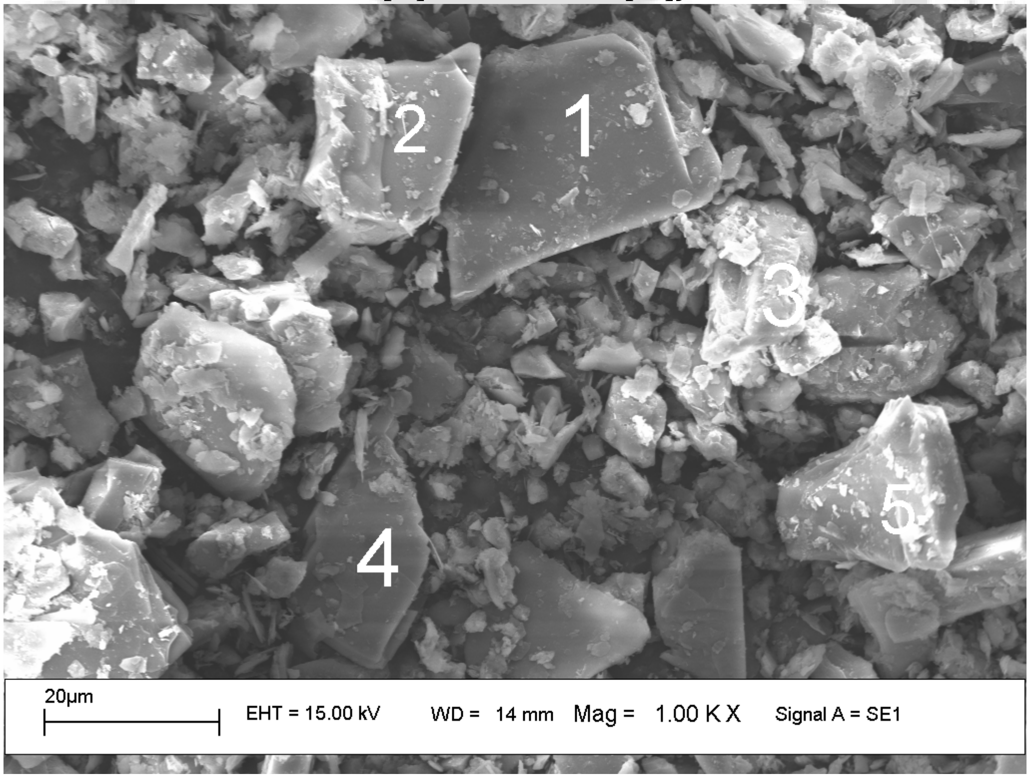


Figure 6.10: SEM image of bed sediments **{1.** Mg-Al-Si-Ca-Fe **2.** O-Na-Al-Si-Ca [**M**] **3 & 5.** O-Si [**Q**] **4.** O-Mg-Al-Si-Ca-Fe [**M**]**}**

transport, agrees with Irion's (1991) observation that original shapes of sediment particles smaller than 1000 μm are not significantly affected during transport.

Elemental analyses by Energy Dispersive X-ray Spectroscopy (EDS) revealed (Figures 6.11 and 6.12) the abundance (wt %) of elements in the suspended sediments as O > Si > Al > Fe > K > Mg > Ca > Na > Cu > Ti and in bed sediments as O > Si > Fe > Al > K > Mg > Ca > Na > Ti.

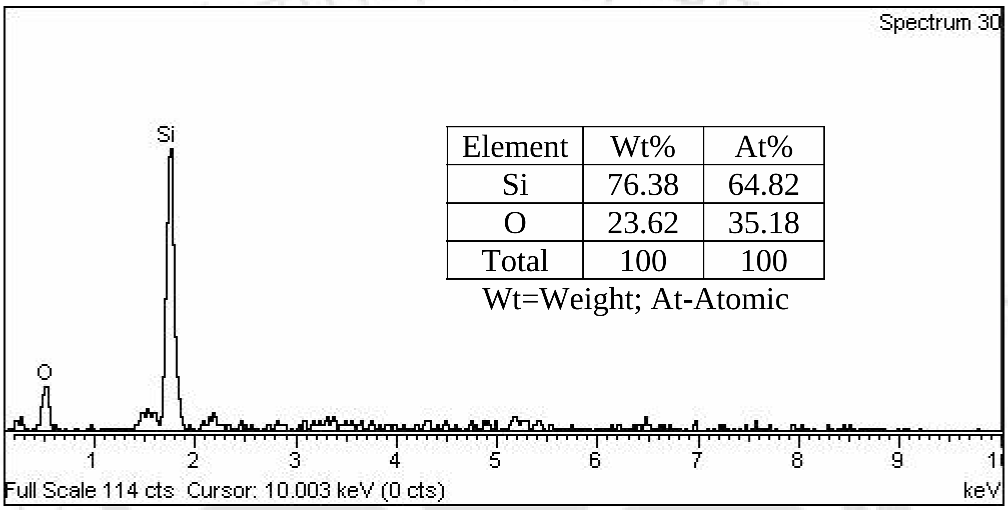


Figure 6.11 A: EDX Spectra and composition of grain 2 (Figure 6.9)

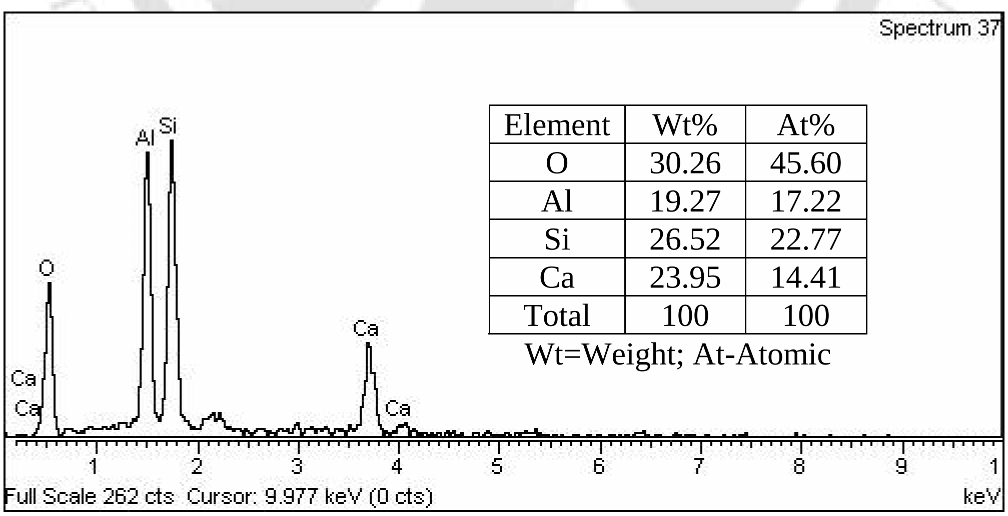
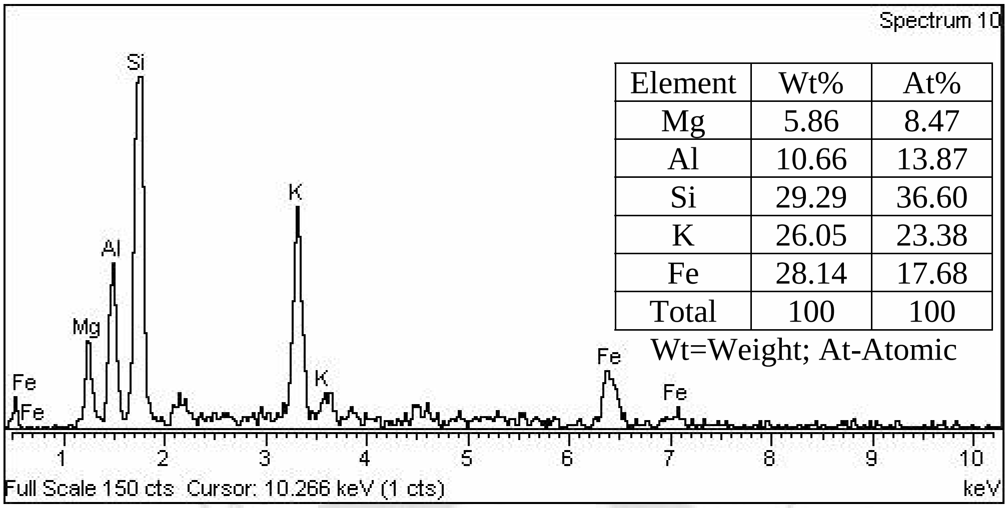


Figure 6.11 B: EDX Spectra and composition of grain 9 (Figure 6.9)



Element	Wt%	At%
Mg	5.86	8.47
Al	10.66	13.87
Si	29.29	36.60
K	26.05	23.38
Fe	28.14	17.68
Total	100	100

Figure 6.12: EDX Spectra and composition of grain 1 (Figure 6.10)

Compositions of the grains prove the presence of the minerals obtained in XRD analyses. Compositions of the labeled grains are furnished under the respective micrographs along with the names of the probable minerals in square brackets. Comparisons of elemental compositions of suspended and bed sediments with Earth Crust composition are shown in Figure 6.13 (Atom %) and Figure 6.14 (Weight %).

Both suspended and bed sediments are depleted in Na and Ca, and enriched in Fe, Si and K in comparison to Earth Crust compositions. These results indicate predominance of chemical weathering in the Brahmaputra basin (Sholkovitz et al., 1978; Subramanian et al., 1985, Manjunatha et al., 1996). High carbonate equilibria in the waters of Indian rivers lower the concentration of Ca in the sediments (Subramanian, 1985). The lower values of Ca and Na in the sediments can be attributed to their greater mobility and easy solubility (Pandey, 2002). Enrichment of Al in the suspended sediments may be due to higher amount of clay minerals (Ramesh, 1985) compared to that in the Earth Crust, which can result from mineralogical conversions in the aquatic environment (Singh et al., 2005).

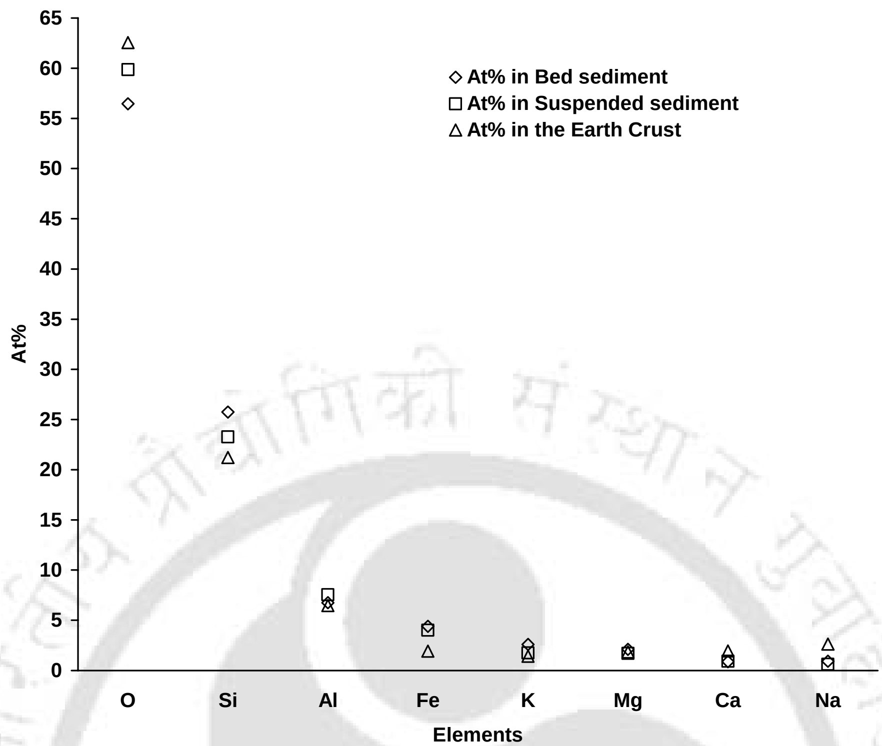


Figure 6.13: Composition (Atom%) of Brahmaputra sediments

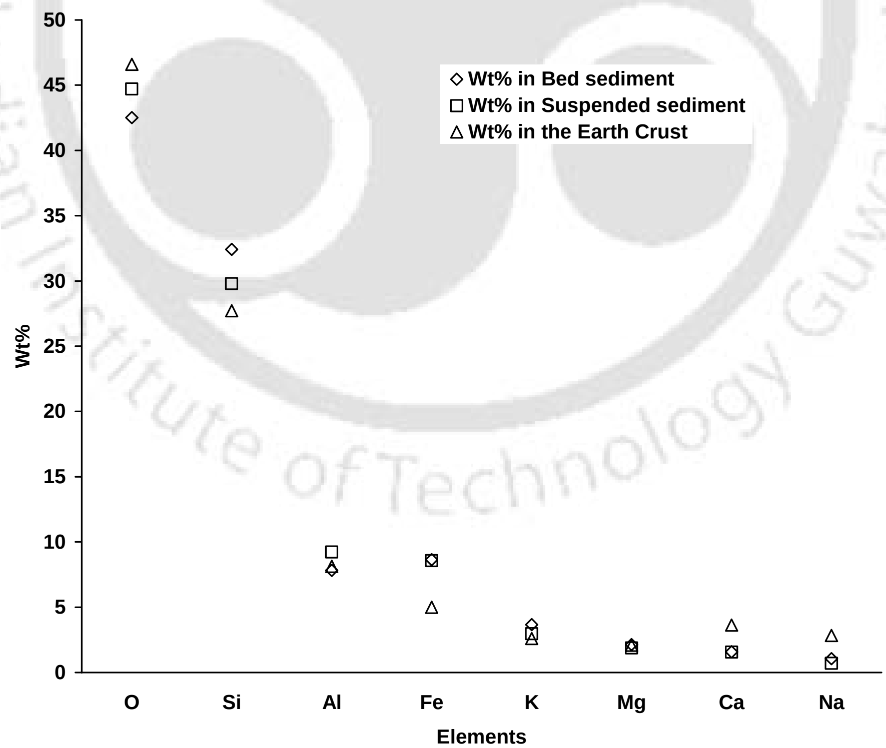


Figure 6.14: Composition (Weight %) of Brahmaputra sediments

Martin and Meybeck (1979) also observed lower concentrations of Ca and Na, and higher concentration of Al in the suspended sediments of tropical rivers. Viers et al. (2009) reported strong depletion of Na in tropical rivers. Thus, results of the present study demonstrate climate as a major controlling factor for compositions of sediments in the Brahmaputra River. Presence of primary ferromagnesian silicates or Fe-rich secondary phases contributes to high Fe concentrations in the suspended sediments (Pokrovosky et al., 2005). In Assam, majority of the soils are made up of iron bearing minerals which is manifested by iron concentration in ground water reaching up to 71 ppm (Jorhat, a district of Assam) (Bharali, 2008). As floodplains also act as sources of minerals to river sediments (Brinkman, 1977; Islam and Lotse, 1986), enrichment of Fe in the Brahmaputra sediments may be attributed to the iron rich soils (Sabri et al., 1993).

Enrichment of K as observed for both bed and suspended sediments in this study may be due to differences in dissolution rates of K_2O in comparison to those of CaO and Na_2O (Hutcheon et al., 2000). Contribution of K by the degradation of mica and other K-silicate minerals may be another reason of K-enrichment in the sediments (Pandey et al. (2002).

6.3. Summary

Sediment, being a product of weathering and erosion will retain the relative abundance of initial mineral composition of the bedrock. But, numerous phases of weathering (mainly chemical weathering), transport, deposition, storage, lithification, reworking and redeposition, may significantly alter the original grain composition (Perry and Taylor, 2007).

TWLSS mineralogy of the Brahmaputra River in the study sites revealed the order of mineral abundance as Quartz > Albite > Illite > Kaolinite > Muscovite > Orthoclase > Chlorite > Montmorillonite. Detrital minerals (quartz, feldspar and mica) constituted about 80% of the total minerals present in the sediments, quartz alone being about 67%. Among feldspars, albite was predominant, which indicated its abundance in the Brahmaputra basin (Singh et al., 2005). Chlorite, illite and kaolinite formed more than 85% of the total clay minerals. Illite and kaolinite were the major clay minerals, which might result from physical weathering of crystalline and metamorphic rocks (Campos et al., 2008) in the Himalayas (Huizing, 1971; Mahanta and Subramanian, 2004). Quantities of minerals revealed high degree of variability. Presence of montmorillonite in most of the sediment samples suggests chemical transformation of aluminosilicates during sediment transport (Fayed, 1970; Singh et al., 2005; Campos et al., 2008), in addition to contribution from volcanic rocks present in the upper drainage basin of the Brahmaputra River. High values of Q:F (Quartz : Feldspar) and Q:M (Quartz : Mica) indicated loss of feldspar and mica due to chemical weathering (Pandey et al., 2002). Low mica contents may also be attributed to the geochemical environments and / or geology of the basin (Heroy et al., 2003). Thus, mineralogy of the sediments supports dominance of both physical and chemical weathering in the Brahmaputra basin. Mineralogical composition of the bed sediment samples did not differ much from that of TWLSS samples, which might be due to similarities in particle sizes of the two classes of sediments (Chapter 5) as mineralogy is usually particle size dependent (Eby, 2004).

Particle shapes of both TWLSS and bed sediment were mostly oblate, prolate or bladed with sharp edges, reflecting their textural immaturity. Abundance (wt %) of elements in the TWLSS was as O > Si > Al > Fe > K > Mg > Ca > Na > Cu > Ti and in bed sediments as O > Si > Fe > Al > K > Mg > Ca > Na > Ti. Both TWLSS and bed sediments were depleted in Na and Ca, and enriched in Fe, Si and K in comparison to Earth Crust compositions, indicating prevalence of chemical weathering taking place in the basin (Sholkovitz et al., 1978; Subramanian et al., 1985, Manjunatha et al., 1996). Enrichment of TWLSS in Al might be due to higher amount of clay minerals (Ramesh, 1985) compared to that in the Earth Crust. Fe enrichment in the sediments points to presence of primary ferromagnesian silicates or Fe-rich secondary phases in the basin. Degradation of mica and other K-silicate minerals enrich sediments in K (Pandey et al., 2002).

CHAPTER 7

EXTRACTABLE METALS IN THE SEDIMENTS OF THE BRAHMAPUTRA RIVER

7. Introduction

The search for a better understanding of trace metal distribution in large river sediments is a major concern in the exogenic cycling of elements through fluvial processes and in assessing the effects of anthropogenic influences. Trace metals adversely impacts microorganisms, plants, animals and humans. So, knowledge of trace metal concentration and distribution in sediments is of fundamental importance in a densely populated and highly agricultural region like the Brahmaputra Basin (Singh et al., 2003).

With an objective of estimating the metal distribution in the Brahmaputra River sediments, ten TWLSS and five bed sediment samples were analysed for extractable concentrations of aluminum, cadmium, chromium, copper, iron, lead, manganese, nickel and zinc following Standard Practices for Extraction of Trace Elements from Sediments (ASTM, 2003).

Chemical compositions of the sediments were investigated using EDS technique (Chapter 6) which, being selective in nature, may not necessarily represent the composition of a sample in totality. Further, the SEM-EDS technique provides data for major elements only, with detection limits of approximately 0.1% (Wagner et al., 2008). Therefore, Atomic Absorption Spectrophotometry (AAS) was used to determine the concentrations of these metals.

7.1. Concentration of metals

Figures 7.1, 7.2 and 7.3 represent the concentrations of the nine metals analysed. Abundance of metals in the sediments in the study area was found as follows:

TWLSS: Al > Fe > Mn > Zn > Ni > Pb > Cu > Cr > Cd

Bed sediment: Al > Fe > Mn > Zn > Ni > Cu > Cr > Pb > Cd

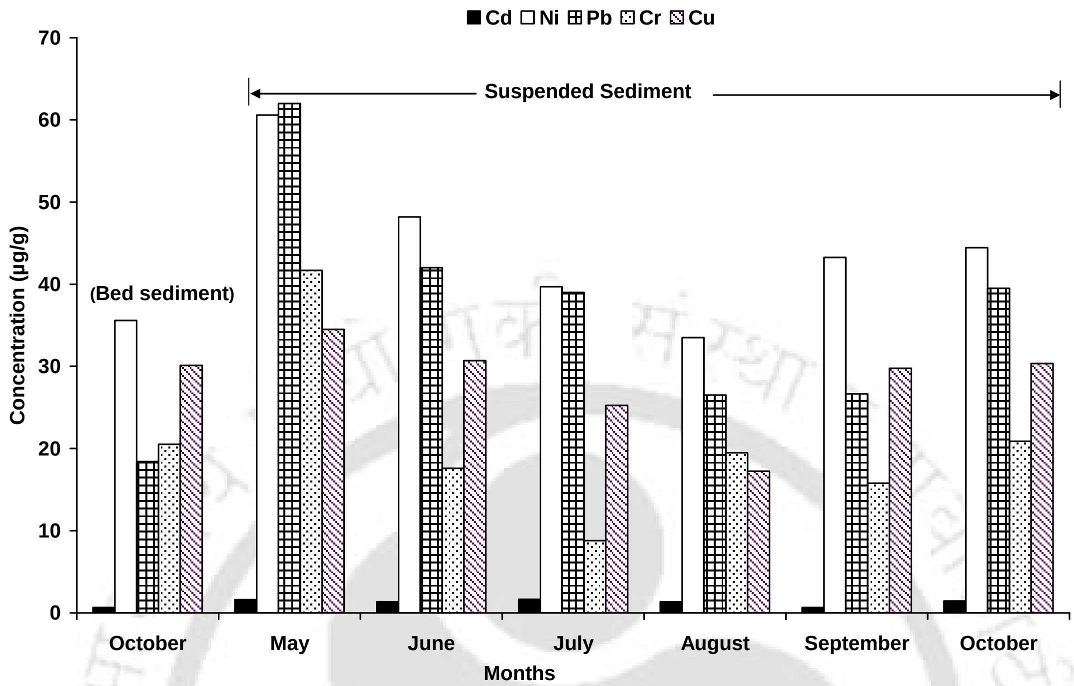


Figure 7.1: Concentration of extractable metals in the sediment

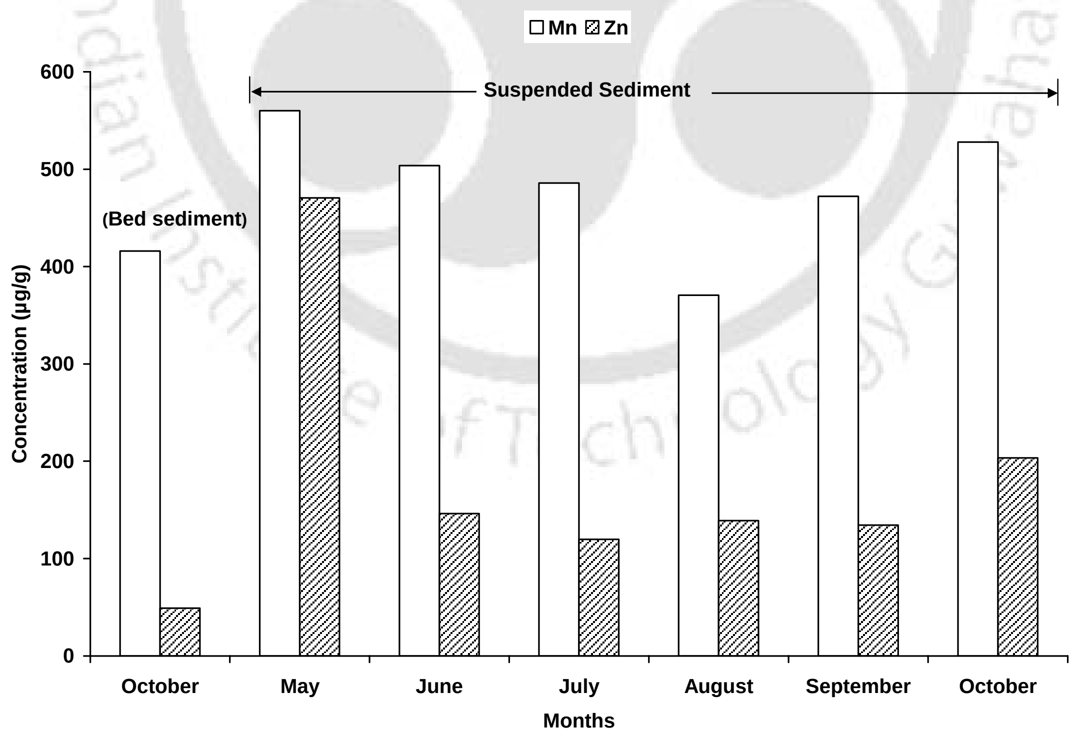


Figure 7.2: Concentration of extractable metals in suspended sediments

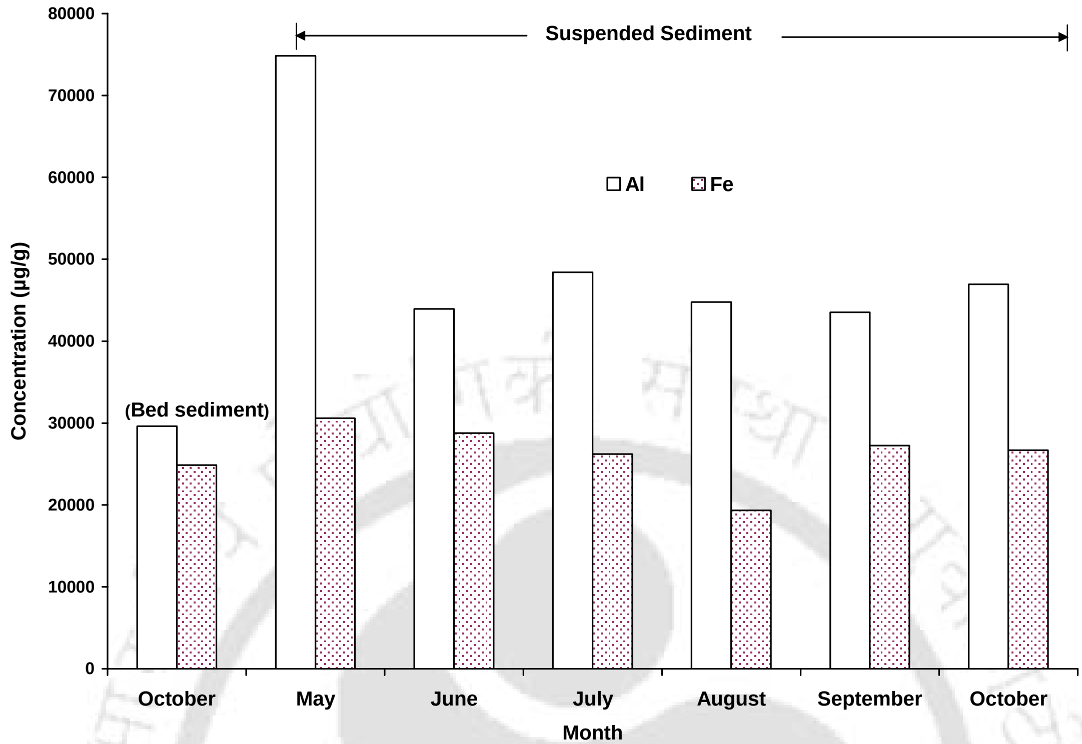


Figure 7.3: Concentration of extractable metals in the suspended sediments

The order of abundance of the metals in the present study was almost similar as that reported by Mahanta and Subramanian (2004) for Brahmaputra sediments (bed and suspended), except for Pb which was higher in concentration in the TWLSS in comparison to Cu and Cr. All the metals except Fe, Cr and Cu showed relatively higher enrichment in TWLSS over bed sediments. The enrichment factors for various metals were as follows: Zn (4.13), Pb (2.13), Cd (2.02), Al (1.70), Ni (1.26) and Mn (1.17). Enrichment factors reported by Mahanta and Subramanian (2004) were higher than those obtained in the present study for Fe, Mn, Cu and Cr and lower for Zn, Pb and Cd. Differences between the results of these two studies can possibly be attributed to differences in sampling procedures, number of samples and time of collection of the samples considered in the respective studies.

Except for Fe and Mn, concentrations of all other metals showed more than 15% coefficient of variations (monthly) which went up to 66.5% for Zn. Minimum value of concentration was observed in the month of August for most of the metals. In the month of May, concentrations of metals (except Cd and Zn) were more than one standard deviation higher than the average. Although fluvial systems are inherently variable and such outlier points are not unusual (Warren and Zimmerman, 1994), further investigations may reveal the specific causes for such occurrences.

Average concentrations of metals in the suspended sediments of the Brahmaputra River found in the present study were compared with those of World Rivers (Viers et al., 2009) and with the upper crust concentration values (Taylor and McLennan, 1985) (Table 7.1). Concentration of metals in the Brahmaputra sediments was found to be lower than those in the World Rivers, which points to a relatively uncontaminated status of this less impacted river.

Table 7.1 Average concentrations of metals (µg/g) in suspended sediments

Metals	Brahmaputra River	World Rivers	Upper Crust Values
Cd	1.34 ± 0.36	1.55 ± 4.15	0.098
Cr	20.72 ±11.12	130 ± 155	35
Cu	27.97 ± 6.02	75.9 ± 135	25
Mn	486.69 ± 64.90	1679 ± 5011	600
Ni	44.95 ± 9.13	74.5 ± 100	20
Pb	39.28 ± 13.01	61.1 ± 91.2	20
Zn	202.21 ± 134.53	208 ± 237	71

Correlations between different pairs of metals have been presented in Table 7.2. Inter-metal correlations provide clues about the “carrier substance” and the chemical association of heavy metals in the basin (Cited by Datta and Subramanian, 1998 from: Forstner, 1981 and Jaquet et al., 1982).

Aluminum showed good correlations with Cd, Pb, Ni, Zn and Mn, moderate correlation with Fe and Cr and little correlation with Cu. Good correlation with aluminum suggests accumulation of metals in association with clays (Datta and Subramanian, 1998). Chen and Wang (1996) attributed the strong relation between trace metal concentrations and aluminum content in the sediments of 12 major rivers in eastern China to the relatively uncontaminated status of the rivers (Cited by Wang and Chen, 2000).

Table 7.2: Inter-element relationship in the suspended sediments (n = 15)

Elements	Cd	Cr	Pb	Cu	Ni	Zn	Mn	Fe	Al
Cd	1								
Cr	0.25	1							
Pb	**0.82**	0.48	1						
Cu	0.09	0.40	0.33	1					
Ni	0.50	0.50	**0.86**	**0.56**	1				
Zn	**0.59**	**0.69**	**0.87**	0.36	**0.86**	1			
Mn	0.46	0.32	**0.74**	**0.67**	**0.85**	**0.74**	1		
Fe	0.31	0.34	**0.58**	**0.82**	**0.79**	**0.56**	**0.86**	1	
Al	**0.52**	0.47	**0.82**	0.02	**0.75**	**0.88**	**0.57**	0.32	1

Cu and Fe showed good correlations with quartz [r = 0.74 for Cu (p = 0.018), 0.62 for Fe (p = 0.05); Figure 7.4) which might explain the superior correlation between Cu and Fe (r = 0.82; p = 0.0063; Table 7.2).

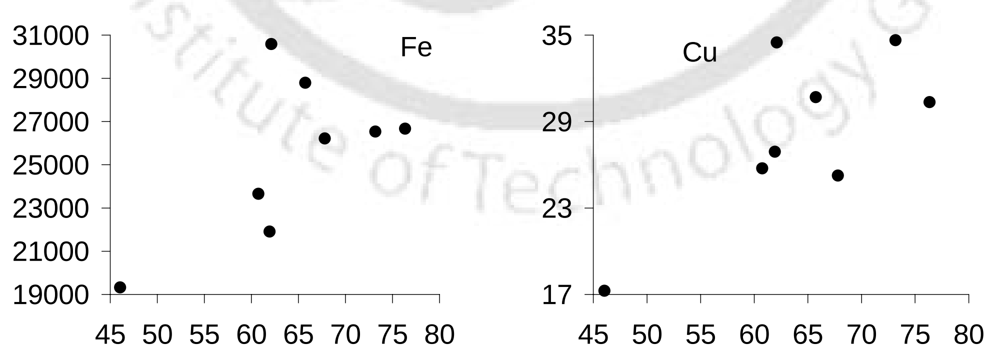


Figure 7.4: Metal concentration (µg/g) as a function of quartz content (%; Hz-axis)

According to the theory of surface complexation, solid surface in solution is negatively charged under the condition of pH > pH_{pzc} (pH of zero charge) and positively charged while pH < pH_{pzc} (Wen et al., 2001). Silica (SiO_2: pH_{pzc} ~ 2) has a great tendency to lose protons and is negatively charged over most of the pH ranges (Gregory, 2006). The average pH of the Brahmaputra water (~8, e.g. Mandal, 2005) exceeds the point of zero charge of SiO_2 and hence its surface should be negatively charged, favouring metal adsorption by electrostatic attraction. This might be a reason for the good correlation of quartz with Cu and Fe. Further, both quartz and metal contents were found to be low in the month of August in the present study, which might point to association of these metals with quartz mineral. However, many authors (Jha et al., 1990; Singh et al., 2003; Selvaraj et al., 2004) ascribed low concentration of metals in sediments to high quantity of quartz in them. Siepmann et al. (2007) observed in laboratory experiments that Cu was mainly adsorbed to algal cell walls representing organic part of the sediment, with negligible amount to quartz and clay, and a small fraction to Fe-Mn oxides. The positive correlation of quartz with Cu and Fe, therefore, might be due to a result of the relation between these metals and FeOOH, MnOOH and / or organic matter, which are coated on sediment grains enriched in quartz (Wang and Chen, 2000). Speciation studies (could not be done in this study) is necessary to determine the geochemical phases to which these metals are actually associated with.

Concentrations of metals in sediments generally increase with clay mineral content (Jha et al., 1990 and 1993). In case of Brahmaputra sediments, most of the metals did not show significant correlations with clay minerals, except Cr, Zn and Al [(r, p) = (0.55, 0.08), (0.41, 0.16) and (0.45, 0.13) respectively], indicating their little role in metal adsorption. This might be due to low level of clay minerals (Syvitsky, 2007) in the Brahmaputra sediments which can be inferred from low amount of clay-sized sediments (Figures 5.7 and 5.8) as quantity of clay mineral in sediments increases with increasing amount of clay-sized sediments (Jha et al., 1993). Poor correlations of clays with metals might also be due to low montmorillonite content (~14% of the total clay minerals; Table 6.1) (Jha et al., 1990), which possesses the highest cation exchange capacity (80-100 meq / 100g; Deutch, 1997) among clay minerals. Moreover, surface of available clay minerals might have little access to sorb metals due to masking of the surface by sorbed FeOOH, MnOOH and organic matter (Jenne, 1968), thereby resulting in the poor correlation. According to Siepmann et al. (2007), ion exchange capacity of clay minerals maximize at pH 5, so higher pH in the Brahmaputra River (average pH = 8 ; e.g. Mandal, 2005) may be another reason for low adsorption of metals to clays. Modak et al. (1992) reported that the order of adsorption characteristics of most of the mobile metal fractions was Fe/Mn oxide > organic > clay.

Good correlation between Fe and Mn ($r = 0.86$; $p < 0.0001$) is explained by their similar sedimentary behaviour (Krauskopf and Bird 1995). Good to excellent positive correlation ($p < 0.05$ mostly) of majority of the metals with Al, Fe and Mn suggests the importance of clay minerals and Fe-Mn oxyhydroxides in accumulating the metals (Datta and Subramanian, 1998). Good correlations between elements indicate their common source, mutual dependence and identical behaviour during transport (Gadh et al., 1993; Jain et al., 2005). Speciation studies are necessary to know the amounts adsorbed by various geochemical components.

Negative correlations ($p = 0.04$ to 0.16) were observed between suspended solids and metal concentrations (Figure 7.5). Similar results were also reported by Sabri et al. (1993) in a study of the Tigris River sediments. They provided no explanations for this phenomenon but asserted the need for investigations on particle size-metal concentration relationships to understand the causes. In the present study, negative correlation was observed between suspended solids concentration and specific surface area (Figure 5.20). Since finer particles adsorb higher amounts of metals, the negative correlation between suspended solids and metal concentrations are implied from the particle size-suspended solids concentration relationship. Other metals in this study also showed negative correlations with suspended solid concentrations, but the correlation coefficients were low (less than 0.4; Allan and Brunskill, 1976).

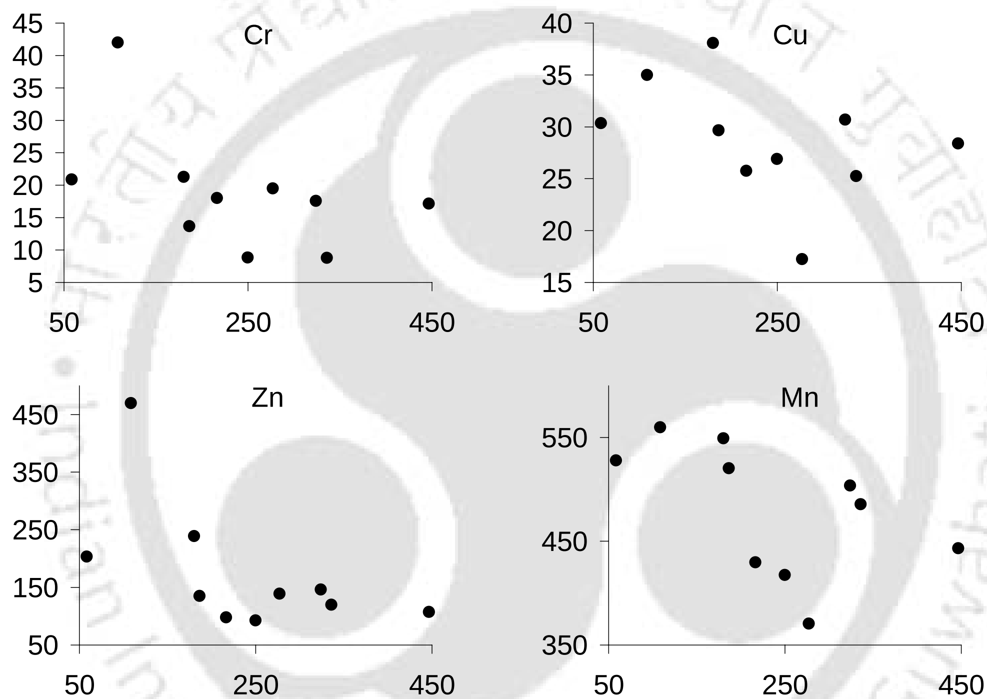


Figure 7.5: Metal concentration (μg/g) as a function of suspended solids concentrations (mg/L; Hz-axis)

Except iron, all the metals showed positive correlations with specific surface area (SSA) and correlation coefficients for aluminum (0.83; $p = 0.001$) and zinc (0.63; $p = 0.008$) were the highest (Figure 7.6). Insignificant correlation of Fe with SSA ($p = 0.43$) suggests that concentration of Fe is controlled by a combination of geochemical support phases (e.g., adsorption at particle surfaces, occlusion in amorphous materials; Gomez-Ariza et al., 1999) and their mixed associations (Jain et al., 2005). Organic matter sorption to oxides decreases substantially at pH values greater than 7 (Tipping, 1986), while Fe uptake by bacteria increases with increasing pH values (Ferris et al., 1989) (cited by Warren and Zimmerman, 1994). As pH values of the Brahmaputra water are usually greater than 7.5 (average pH ~8; Mondal, 2005), insignificant correlation of Fe with SSA might be due to its uptake by bacteria. Concentrations of extractable metals in sediments are significantly controlled by organic matter in reducing environments where concentrations of Fe and Mn hydrous oxides are low (Gaiero et al., 1997). Particle size characteristics of the sediments indicate existence of sufficient turbulence at the sampling site (Chapter 5). Turbulence increases oxygen level in the water (Evans and Davies, 1994; Ciszewski, 1998) leading to precipitation of oxides of Mn and Fe onto the larger grains due to increased redox potential (Carpenter and Hayes, 1978; Ciszewski, 1998). When no organic matter is present, the effect of a strong bond between Zn and Mn oxides is very marked (Filipek et al., 1981). Correlation of Zn with SSA may be explained by its adsorption to Mn oxides coatings on sediment particles at an oxic environment where organic matter plays insignificant role in adsorption due to high pH (Tipping, 1986 cited by Warren and Zimmerman, 1994). Determination of organic matter and Fe-Mn oxides in the sediments might have helped to evaluate their respective roles in adsorption.

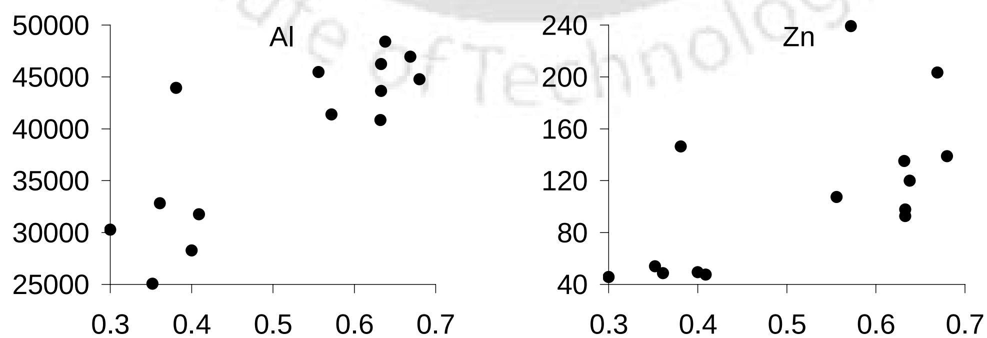


Figure 7.6: Correlations between specific surface area (m^2/g; Hz-axis) and metal concentrations (µg/g)

Clay minerals contain aluminum in their compositions and are generally found more in the finer (clay sized) fractions of sediment (Jha et al., 1993). Finer sediments having large SSA, positive correlation between aluminum and SSA is likely.

Many authors have reported clay and silt as the major fractions in sediments to contain metals (e.g., Krumgalz et al., 1992; Jain and Ram, 1997; Johnson et al., 2005). Metal concentrations in the Brahmaputra sediments were found to correlate negatively with clay-sized and sand sized sediments, and positively with silt sized sediments (Figures 7.7 A to 7.7 D) with the exception of Aluminum (Figure 7.7 E). Selvaraj et al. (2004) observed negative correlation of Si with metals (Al, Fe, Mn, Cr, Cu, Ni and Zn) and citing Buckley and Winters (1992), ascribed their observations to dilution of particulate trace metals by sandy, detrital sediments. Bulk sediments including clay-sized fraction being predominated by high quartz content and considering the preferential deposition of Fe-Mn oxides on relatively larger grains (Carpenter and Hayes, 1978; Ciszewski, 1998), negative correlation of clay-sized fraction with metal concentration is likely. Jana (2005) observed high negative correlation between clay-sized sediments and metal concentrations in sediment samples collected near the sampling sites of the present study. According to him, the metals in clay-sized sediments were contributed mostly by the residual fractions (embedded in the crystal lattice) and adsorption played little role in controlling the concentrations of metals in sediments.

As explained above, the hydrodynamic conditions in the sampling sites were conducive to precipitation of Fe and Mn oxides on the sediment particles, which possess high adsorptive capacities due to their large specific surface areas (Warren and Zimmerman, 1994). The positive correlation between silt and metal concentrations is likely to be due to adsorption of the metals on the oxide-coatings formed on the silts, which was the major fraction (Figures 5.7, 5.8) of the sediments in the present study (Syvitsky, 2007).

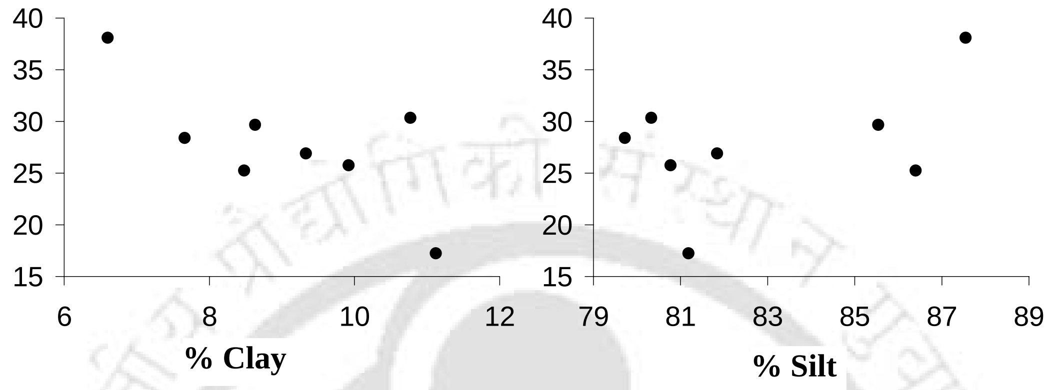


Figure7.7 A: Variations of Cu (μg/g of sediment) with clay (p=0.02) and silt (p=0.12)

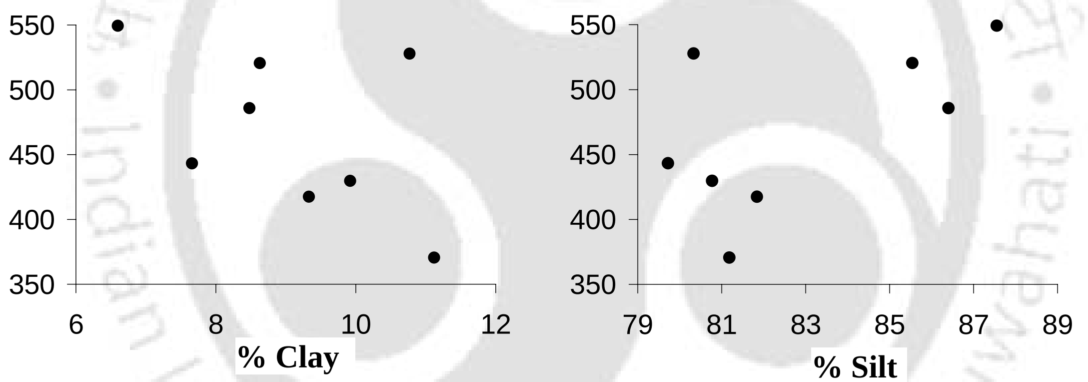


Figure 7.7 B: Variations of Mn (μg/g of sediment) with clay (p=0.09) and silt (p=0.05)

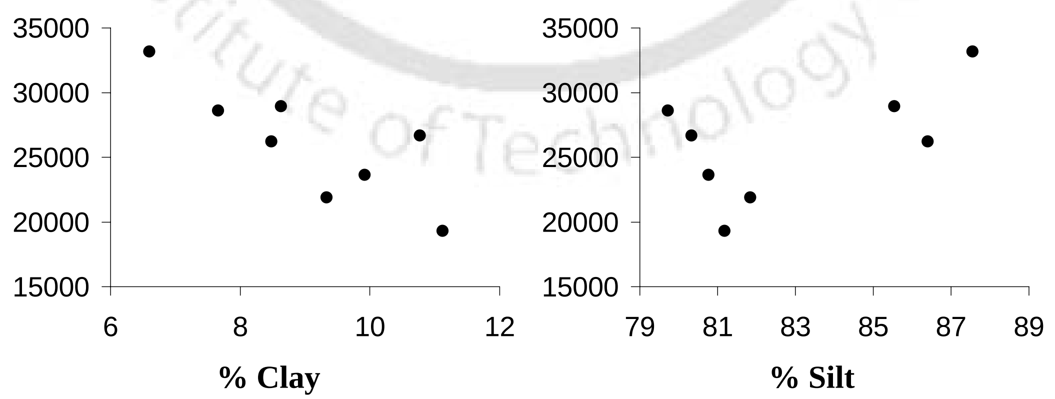


Figure 7.7 C: Variations of Fe (μg/g of sediment) with clay (p<0.01) and silt (p=0.07)

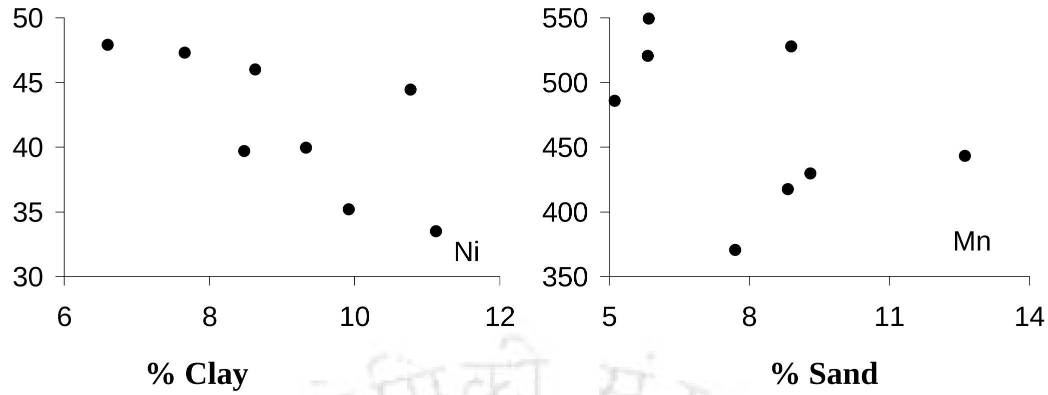


Figure 7.7 D: Variations of Ni and Mn (µg/g of sediment) with clay (p=0.02) and sand (p=0.14)

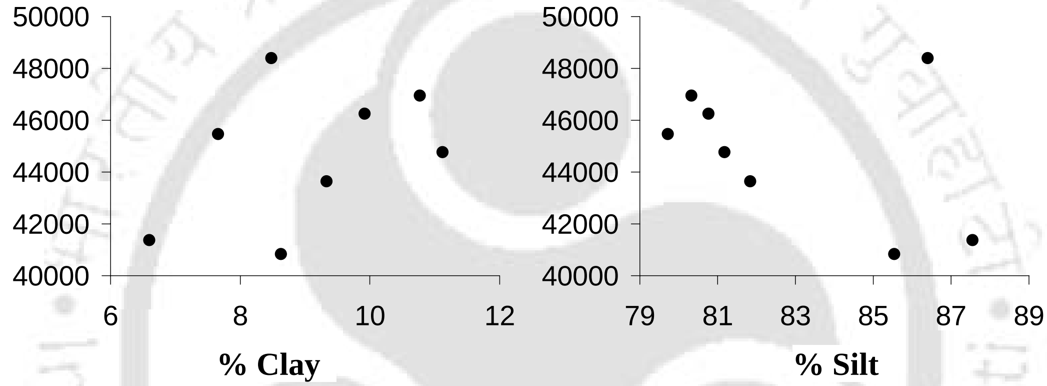


Figure 7.7 E: Variations of Al (µg/g of sediment) with clay (p=0.15) and silt (p=0.15)

Larger grain size and dilution of particulate trace metals by detrital nature of sand are the possible reasons to produce negative correlation between sand content and metal concentrations (Figure 7.7 D) in sediments (Horowitz, 1985; Selvaraja, 2004).

Increase of clay minerals (which have aluminum in their compositions) with clay-sized sediments (Jha et al., 1993) is a likely reason for the positive correlation between clay-sized sediments and aluminum. Negative correlation between silt and aluminum indicates low level of clay minerals in the silts (Figure 7.7 E).

7.2. Summary

The order of abundance of metals in the Brahmaputra sediments was found to be as follows:

TWLSS: Al > Fe > Mn > Zn > Ni > Pb > Cu > Cr > Cd

Bed sediment: Al > Fe > Mn > Zn > Ni > Cu > Cr > Pb > Cd

Except Cu, all other metals showed enrichment in TWLSS over bed sediments. The enrichment factors for various metals were as follows: Zn (4.13), Pb (2.13), Cd (2.02), Al (1.70), Ni (1.26), Mn (1.17), Fe (1.07), Cr (1.01).

Concentrations of metals in TWLSS were found to be lower than average values for suspended sediment of the World Rivers, which indicated a relatively uncontaminated status of the river. Positive correlation of Al with most of the metals further reinforced this inference (Chen and Wang, 1996). Types of correlations of quartz, clay minerals and silts with metal concentrations indicated likely coating of sediment particles with Fe-Mn oxides and organic matters, which seemed to control metal adsorption on to the sediments. Good correlations between Fe and Mn and most of the analysed metals also substantiated the importance of Fe-Mn oxides in accumulating metals. Negative correlations were observed between TWLSS and metal concentrations, which indicated dilution of particulate trace metal by quartz (Selvaraj et al., 2004) at elevated TWLSS concentrations, considering the fact that quartz was the dominant mineral (~67%) in the sediments. Only Al and Zn showed good correlations with specific surface areas. Positive correlations of Al with SSA indicated presence of more clay minerals in finer sediments, which was reported by other authors as well (Jha et al., 1993). Poor correlations between clay minerals and metal concentrations in the Brahmaputra sediments pointed towards other factors (e.g., coating of sediment particles by oxides of Fe-Mn) having control over metal adsorption (Jain et al., 2005). Correlation of Zn with SSA points towards influence of Mn oxides in the adsorption of Zn, since conditions favourable for this association to occur were indicated by the particle size characteristics of the suspended sediments. Like some other studies (e.g., Jana, 2005), negative correlations were observed between clay-sized sediments and metal concentrations in the suspended sediments of the Brahmaputra River as well. Analyses of a larger sample population drawn from all over the basin can help to reinforce inferences drawn from the current work more conclusively.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8. Introduction

In the present study, characteristics of the sediments transported by the Brahmaputra River (TWLSS- Top Water Layer Suspended Sediment and bed sediments) were investigated along a cross-section with the help of primary data generated using Particle Size Analyser, X-Ray Diffractometer, Scanning Electron Microscope equipped with Energy Dispersive X-Ray and Atomic Absorption Spectrophotometer to characterise the nature and properties of the sediments for their current and future implications. Water discharge (Q) data (15th May 2001 to 15th October 2008) and depth-integrated suspended sediment concentration (C) data (1st December 2003 to 15th October 2008) obtained from Central Water Commission (CWC), Middle Brahmaputra Division, Government of India, were complemented with the primary data to further examine the aspects and trends concerning sediment flux in the river, C-Q relationships, and for estimation of total sediment load. The chemical compositions of sediments were also evaluated to understand the nature of particulate metal flux by them.

8.1. Results and their implications

Annual sediment loads of the Brahmaputra River was observed to be in the range of 259 to 483 million tons/yr (445 to 832 tons $km^{-2}.yr^{-1}$) at the sampling sites, out of which fine (< 75 µm), medium (75-200 µm) and coarse (>200 µm) fractions constituted 86-194 (43.2 %), 83-154 (36.3 %) and 60-71 (20.5 %) million tons/yr respectively. During December to May (averages of monthly sediment loads in the period from 2003 to 2008), fine fraction was higher than the combined load of coarse and medium fractions. Dominance of fine fractions in the sediments indicated prevalence of chemical weathering in the Brahmaputra basin.

TWLSS concentrations during monsoon months was found to be higher particularly towards south bank of the river, apparently due to the slow cross-channel mixing of tributary inputs of sediments and/or due to strong turbulence and eddying prevalent in this part of the river. This suggested a heterogeneity in the profile of sediment distribution along the cross-section investigated and can have implication to installation of different infrastructures such as location of ongoing drinking water intakes for the 107 MLD South Guwahati West Water Supply scheme and navigational facilities like jetties being currently built in the area including possibility of river bank aggradation and channel modification bearing consequential economic repercussion for current and future projects since the adjoining area is being developed as a major river port.

About 65% of the total annual water discharge occurred during the monsoon months (June to September). More than 80% of the total annual sediment load was found to be transported in the monsoon months while very low amount (~ 2 %) got transported in the winter months. Recognition of these fluctuations exhibited by sediment transport can facilitate setting up suitable sediment monitoring strategies (Meybeck, 2001), for example, by carrying out more intensive sampling during the monsoon months for emerging problems like particulate contaminant transport. Considering the fact that most of the suspended sediments are transported during high flow events, Carter et al. (2003) carried out suspended sediment sampling (the Aire and the Calder Rivers, UK) during those events only. Such sediment monitoring strategy can save both time and resource if planned suitably.

Suspended sediment concentration (C) was found to increase with discharge (Q). C-Q relations usually exhibited a Figure-Eight form of hysteresis, indicating contribution of sediments from both nearby (e.g., flowage failure of river banks: Coleman, 1969; bed sediment resuspension and bank scour: Datta et al., 1999) and distant sources (e.g., the Siang-Tsangpo Rivers: Singh and France Lanord, 2002). Similar pattern of C-Q relation was exhibited by earlier data reported from Bahadurabad in Bangladesh (Coleman, 1969), indicating possibility of such sediment-discharge relationship at other locations of the river as well. Analyses of samples collected at various locations along the river should conclusvely reveal the validity of this conjecture. If this relationship is conclusvely established along different locations of the river, it will help in designing project towards effective sediment management strategies and erosion control measures, since rising or falling discharge wiil provide useful prediction of sediment build up in the flow as well.

The suspended sediment transport in the Brahmaputra River was found to be controlled by flow hydraulics at lower discharges and by supply at higher discharges. This was in conformity with the formation of Figure-Eight form of hysteresis in C-Q relationship. Since the major fraction (> 80%) of the annual sediment load was found to be transported during the monsoon months characterized by higher discharges, suspended sediment in the Brahmaputra River is apparently supply controlled. The predominance of sediment availability from upstream of the basin compared to in-situ availability implies that the major problems of river bed aggradation, river bank erosion and avulsion are attributable to the large amount sediment supply to the channel. Thus, it can be argued that mitigation to the disastrous bank erosion and channel congestion problems of the Brahmaputra River lies in curtailment of sediment supply from the upper catchments, carefully designing such projects without compromising the particulate nutrient load.

Both TWLSS and bed sediments were mesokurtic, normally distributed and poorly sorted. TWLSS particle sizes were occasionally polymodal and gap-graded indicating sediment contributions from diverse sources [e.g., colluvial deposits (Zhang and Chen, 2005); flowage failure of river banks (Coleman, 1969); bed sediments resuspension and bank scour (Datta et al., 1999)]. Grain sizes of TWLSS and bed sediments ranged mostly between 1 to 100 µm and 1 to 1000 µm sizes respectively, while ~ 82% of bed sediments belonged to 1 to 100 µm size range. Average clay contents in TWLSS and bed sediments were about 8.9 % and 4.7 % respectively. While poor sorting of the sediments make them amenable for good compaction, low clay content is likely to hinder binding among the remaining grains making them vulnerable to erosion. Further, although clay deposits are more resistant to erosion, their relatively low availability leads to the lack of major and consistent clay layers in the river bank and resultant additional vulnerability of river reaches to bank erosion which has turned out to be the biggest challenge in the Brahmaputra river.

Particle shapes of both TWLSS and bed sediment were mostly oblate, prolate or bladed with predominantly sharp edges, often reflecting their textural immaturity. Surface textures also revealed angular outlines, fractured blocks, conchoidal breakage, parallel and sub-parallel steps and even surfaces. Dissolution pits and hollows, secondary growth and surface etching visible on the sediment particles could be attributed to the chemical activities undergone by them (Pandey et al., 2002). Texturally immatured sediments with angulairty and edges are known for their damage-causing tangential impinging and direct hammering impacts on hydraulic machineries and structures. Such sediment bombardments particularly during monsoon will require adequate precautionery measures for projects planned in the study area having under-water components .Further, silt was the dominant fraction in both TWLSS and bed sediments. This aspect deserves critical consideration particularly while erecting structures like dam across the river and flood and erosion control infrastructures like embankments and spurs. Silty materials are susceptible to piping and have low tolerance to seepage force (Duncan, 1987).

Cumulative frequency distribution curves for TWLSS grain sizes and C-M diagram revealed either absence of a graded suspension or presence of a thin layer of it at the study area. Considering the dominance of silt, existence of a uniform suspension is likely at the study site. This phenomenon seems to be quite unique as has been reported for the Mississippi River. If this can be established conclusively, there can be modified approach towards understanding the hydraulic behaviour of the river. Sediment sampling and monitoring costs will also be reduced due to possibility of using a larger sampling grid, considering the relative homogeneity of this layer along the river.

Order of mineral abundance in TWLSS was as Quartz > Albite > Illite > Kaolinite > Muscovite > Orthoclase > Chlorite > Montmorillonite, and in bed sediment as Quartz > Albite > Kaolinite > Illite > Chlorite. Detrital minerals (quartz, feldspar and mica) constituted about 80% of the total minerals present in the sediments, quartz alone being about 67%. Illite, kaolinite and chlorite formed more than 85% of the total clay minerals. Illite and kaolinite were the major clay minerals, which indicate physical weathering of the crystalline and metamorphic rocks (Campos et al, 2008) in the upper catchments of the river in the Himalayas. Presence of montmorillonite in most of the sediment samples suggests chemical transformation of aluminosilicates during sediment transport (Fayed, 1970; Singh et al, 2005; Campos et al, 2008), besides contribution from volcanic rocks reportedly present in the upper drainage basin of the Brahmaputra River. High values of

Q:F (Quartz : Feldspar) and Q:M (Quartz : Mica) indicated loss of feldspar and mica due to chemical weathering. Mineralogy of the sediments considered in this study indicated dominance of both physical and chemical weathering in the Brahmaputra basin. Since erosion of hydraulic machines (e.g., turbines) increases with particle size and proportion of quartz present in the sediment, with ~ 67% quartz and, particle size and SSC positively correlated, the sediment at higher concentrations will adversely erode hydraulic machines. Adoption of special measures such as preventive coatings will be necessary for mitigating this.

Abundance (wt %) of major elements in the TWLSS was in the order O > Si > Al > Fe > K > Mg > Ca > Na > Cu > Ti and in bed sediments as O > Si > Fe > Al > K > Mg > Ca > Na > Ti. Both TWLSS and bed sediments were depleted in Na and Ca, and enriched in Fe, Si and K compared to Earth Crust compositions, indicating prevalence of chemical weathering in the basin. Enrichment of TWLSS in Al might be due to higher amount of clay minerals compared to that in the Earth Crust. Fe enrichment in the sediments points to the presence of primary ferromagnesian silicates or Fe-rich secondary phases in the basin. Degradation of mica and other K-silicate minerals enrich sediments in K (Pandey et al, 2002). The understanding of the sediment composition indicates that the geochemical evolution of the river is still quite natural with no significant impact from anthropogenic activities.

Abundance of trace metals (µg / g) in the TWLSS was in the order Al > Fe > Mn > Zn > Ni > Pb > Cu > Cr > Cd and in bed sediment as Al > Fe > Mn > Zn > Ni > Cu > Cr > Pb > Cd. Almost all the metals showed further enrichment in TWLSS over bed sediments. The enrichment factors for various metals were as follows: Zn (4.13), Pb (2.13), Cd (2.02), Al (1.70), Ni (1.26), Mn (1.17), Fe (1.07), Cr (1.01). Adsorption of metals on sediments was apparently controlled by Fe-Mn oxides and organic matters.Trace metal concentrations in TWLSS were found to be lower than their average values in suspended sediment of the World Rivers, indicating a relatively uncontaminated status of the Brahmaputra River which suggested that the sediments do not currently pose a threat either as source or sink of toxic metals.

8.2. Future scope

Following aspects may be further investigated by analyses of samples collected at regular intervals from all over the basin, for a better understanding of the behaviour of the sediments in the Brahmaputra River; some of which have been revealed in the present study:

- C-Q relations at different cross-sections of the river to establish a river-wide behaviour
- Possibility of absence of graded suspension and presence of a thick uniform suspension of sediments all along the river
- Correlations of trace metals with clay-sized sediments, clay minerals and silts. Negative correlations of trace metals with clay minerals and clay-sized sediments needs careful investigation. Size-fractionated study will be useful for a proper understanding of these behaviors.
- Simulation studies to understand the precise nature of implications of the findings of the present study, particularly with respect to influence on planned infrastructure in the study area.

8.3. Possible limitations of the present study

It was possible that turbulence at the vicinity of the TWLSS sampling sites was higher than at other locations away from the bridge due to (a) the wake vortex generated by the bridge piers at the downstream side and (b) higher velocity - as the section is narrower and deeper. It is likely that the high turbulence may churn up bed materials into suspension, thereby influencing the TWLSS. The bed sediment samples were collected from a shallow depth (50-60 cm). The velocity of flow was low which may result in bed sediments to be of finer constituency than the normal. Hence, results of the present study may appear not to represent general nature of the sediments. However, the following points may be worth considering about influence of turbulence on the TWLSS:

- To minimise the influence of turbulence on TWLSS, a fair amount of distance was kept (to avoid the wake vortices) from the piers while sampling.
- Silt was the dominant fraction in the TWLSS. Silt forms uniform suspension in rivers (Morris And Fan, 1998). C-M diagram supported existence of uniform suspension of TWLSS in the sampling site. About 82% of the bed sediments fell in the TWLSS size range (1-100 μm). Based on the observations of Walling et al. (2000), it can be inferred that transports of TWLSS (Figure 5.21) and depth integrated suspended sediment (Figure 5.22) were mostly supply controlled, which is also in agreement with the observations of various authors on the major sources of sediment in the Brahmaputra River (Singh and France-Lanord, 2002; Datta and Singh, 2004). All these observations indicate that concentration and particle size of TWLSS should not be significantly influenced by turbulence. Again, a photograph (Figure 5.13) of the excavated braid bar, near which the bed sediment samples were taken, revealed almost only silt deposits up to about 2 m thickness. So, there is a high probability of churning up only silts by the turbulence. While median size of the TWLSS particles was 14 μm, 99% of those were finer than 133 μm. The corresponding values for bed sediments were 33 μm and 588 μm respectively.

- Mineralogy and composition of sediments depend on parent rock properties (Heroy et al., 2003). Again, quantity of metals in sediments depends on mineralogy and particle size of the sediments (e.g., Horowitz, 1985; Wang and Chen, 2000; Fontaine et al., 2000; Syvitsky, 2007). So mineralogy, composition and metals in the sediments should not be affected much by turbulence.

Thus the results for TWLSS should bear the general characteristics of the sediments in the top 1 m water layer of the river.

There were close similarities between values of some parameters (Table 8.1) observed in the present study and those reported by Goswami (1985) for samples collected at Pandu, a place about 200 m upstream of the present study sampling site. This shows on one hand that nature of sediment characteristics has remained by and large consistent over this period of time, which is expected due to the fact that no major land-use changes including construction of dam and reservoir have occurred during this time and that the bed sediment samples collected in the present study bear close similarity to the general bed sediments of the Brahmaputra River. Although the bed sediment samples were collected in a comparatively calm portion of the river, the samples appeared to have received negligible influence from the TWLSS and thus possessed the general characteristics of the Brahmaputra River bed sediments.

Table 8.1: Comparison of results of this study with those of Goswami (1985)

Parameters	Values observed in the present study	Values reported by Goswami (1985)
Median size	33 μm	30 μm
Clay content	4.7%	< 5%
Fine sand-silt content	89.5%	Mostly

Further, the fact that the bed sediments were collected from the central part of the river and not from near the banks, perhaps justify the comparison between TWLSS and bed sediment samples although these were not collected exactly from the same spot.

From these discussions, it may be argued that, although the sampling was restricted to a small location due to logistic constraints, there is a likelihood that the results of the present study may as well be representative of the general characteristics and behaviour of the study area and possibly the sediments of the Brahmaputra River in general. It will be interesting to see if future studies can prove or disprove it to be so.

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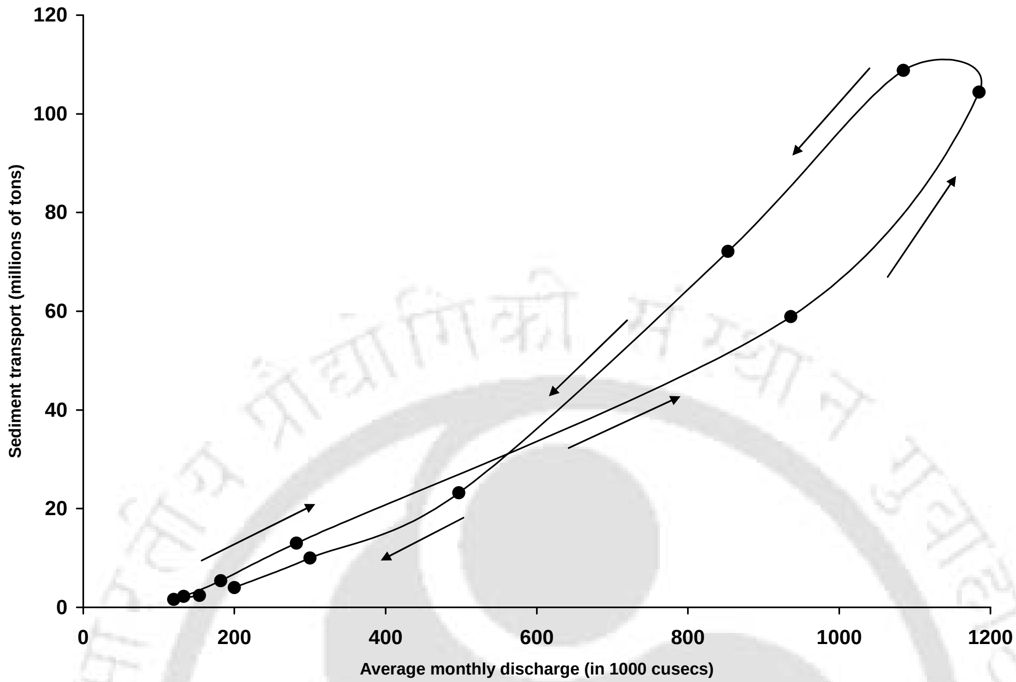
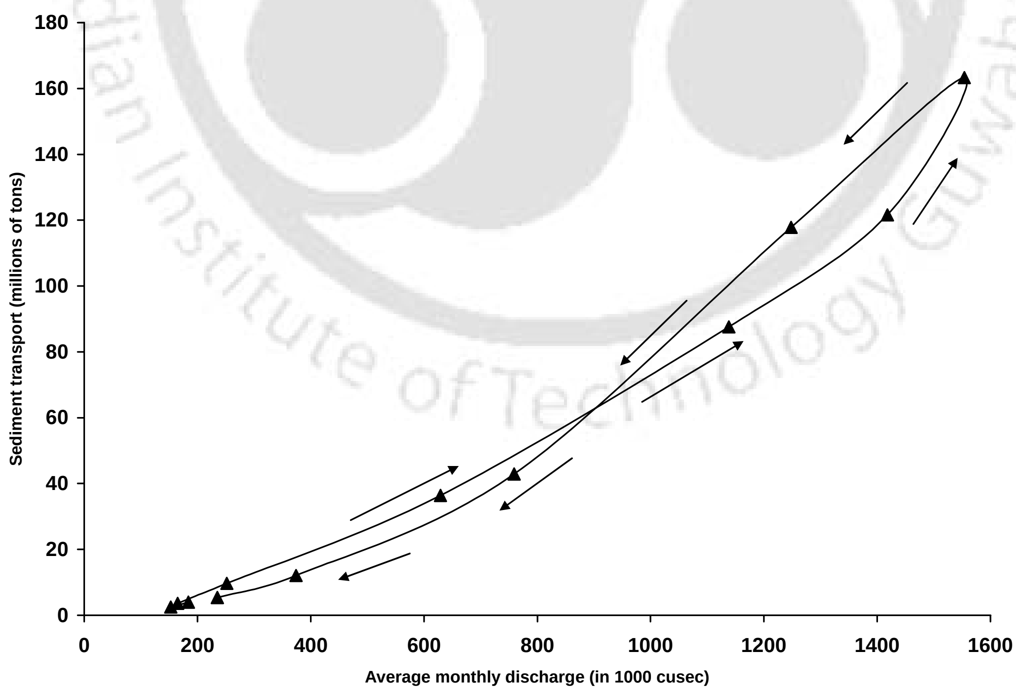
APPENDIX

APPENDIX-I

[Figure-Eight shape in <u>water discharge-sediment load</u> plots in the Coleman (1969) data]

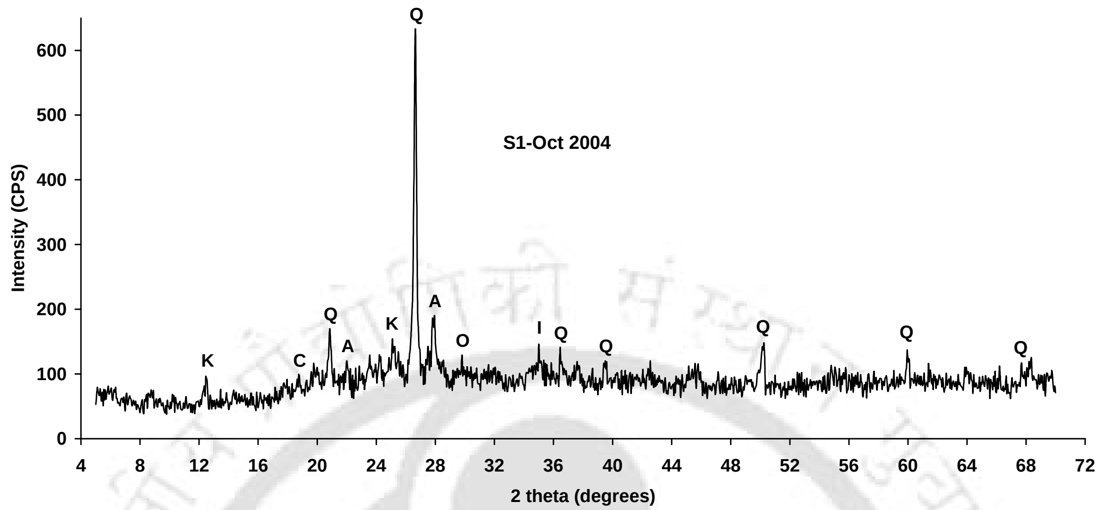


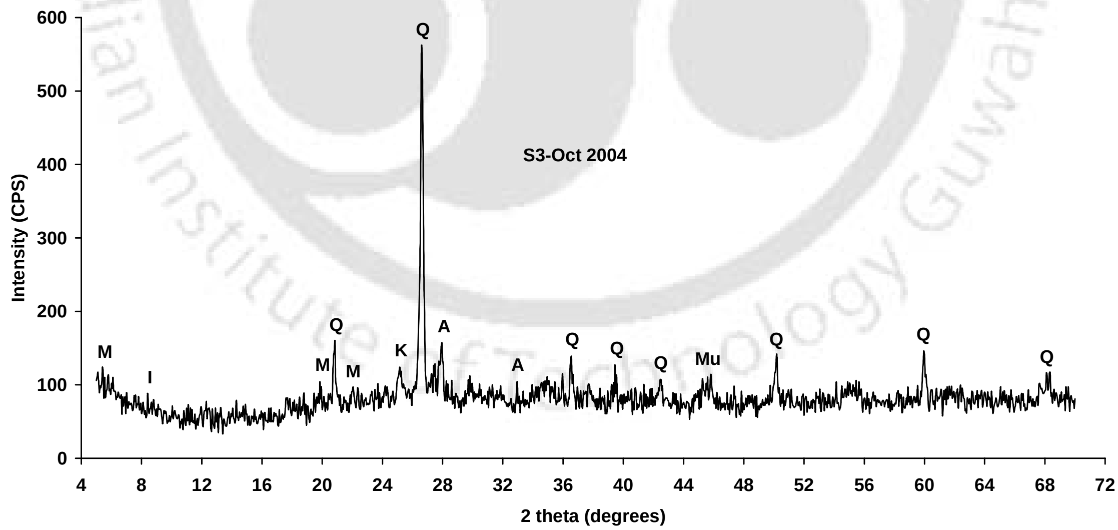
<u>Plot for minimum values in the Coleman (1969) data</u>

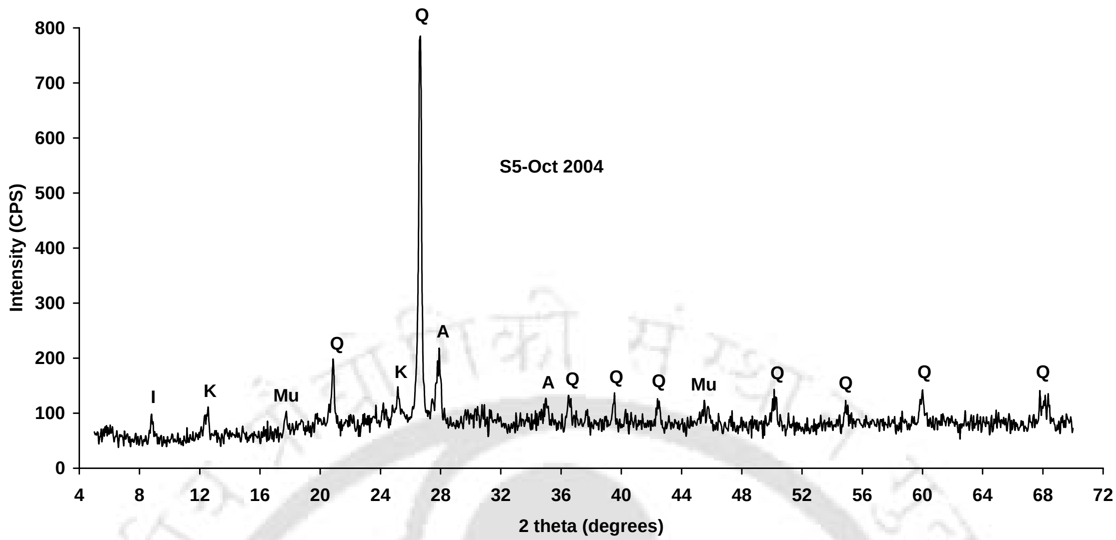


<u>Plot for mean values in Coleman (1969) data</u>

[X-Ray Diffractograms (S1, S2, S3, S4 and S5 are sampling locations)]



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800
700
600
500
400
300
200
100
0
Intensity (CPS)
S5-Oct 2004
I
K
Mu
Q
K
A
A
Q
Q
Q
Mu
Q
Q
Q
Q
4
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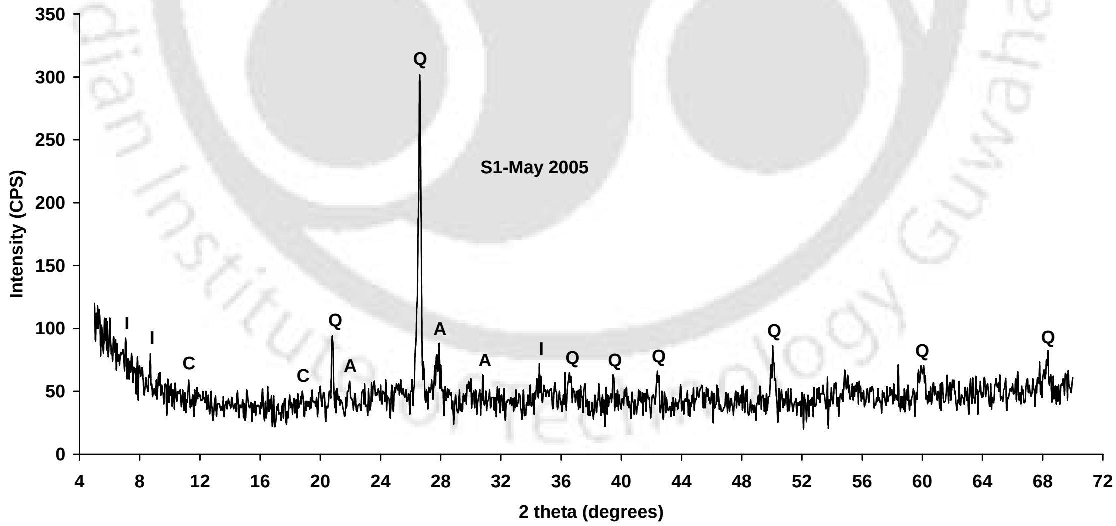
68
72
2 theta (degrees)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300
250
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150
100
50
0
Intensity (CPS)
Q
S1-May 2005
I
I
C
C
Q
A
A
A
I
Q
Q
Q
Q
Q
Q
4
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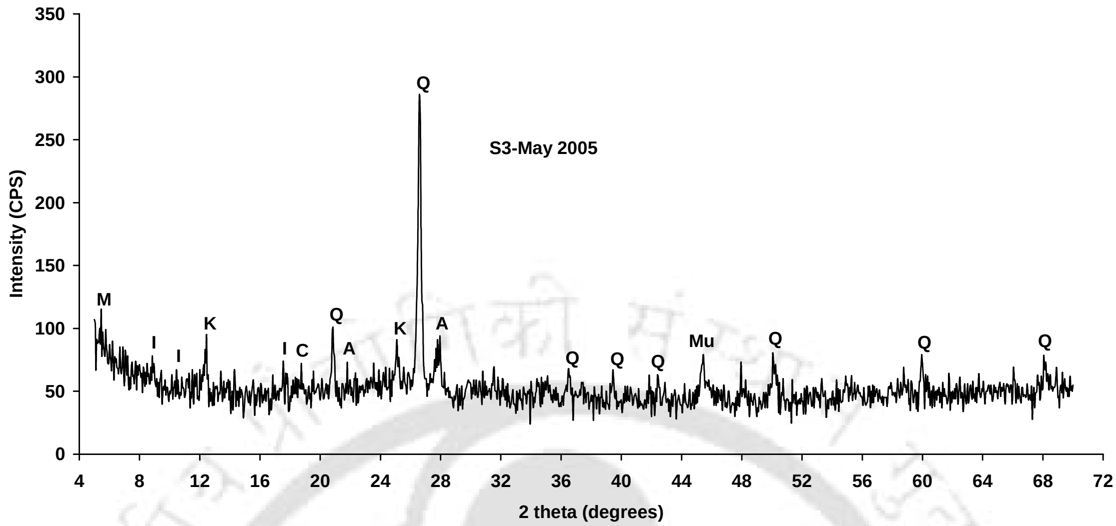
68
72
2 theta (degrees)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Intensity (CPS)
2 theta (degrees)
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I
I
K
I
C
Q
A
K
Q
A
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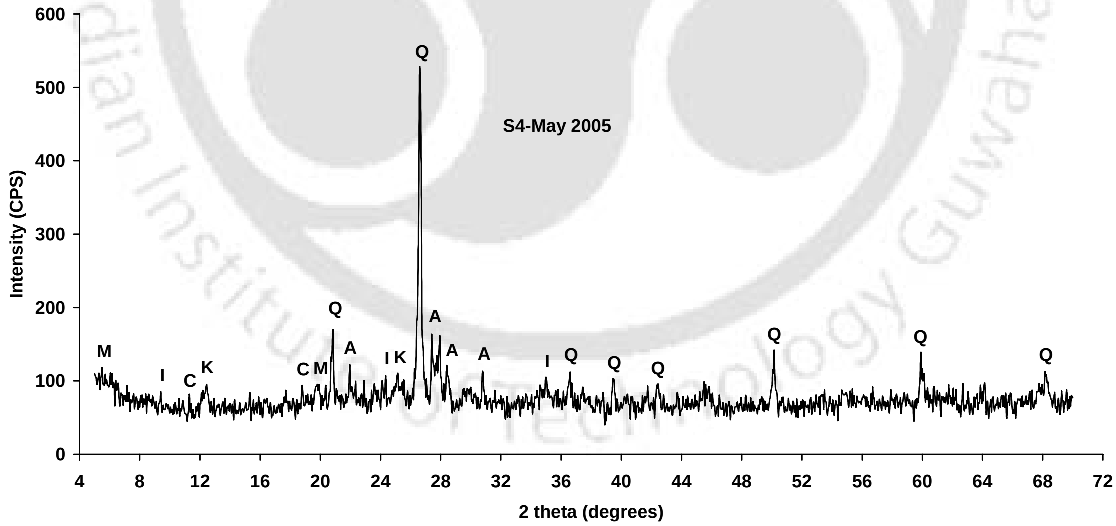
Q
Mu
Q
Q
Q


S4-May 2005
Intensity (CPS)
2 theta (degrees)
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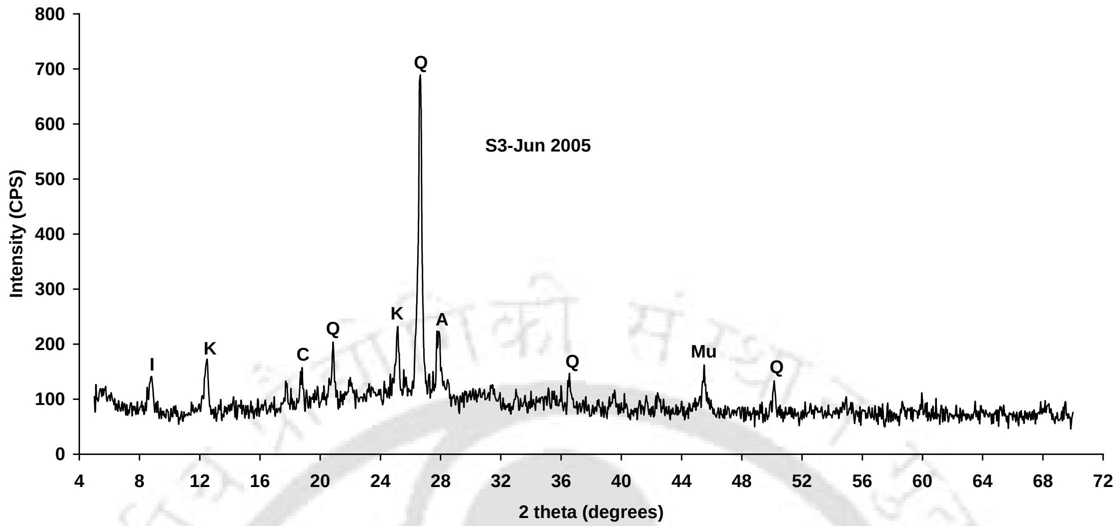
I
C
K
C M
Q
A
I K
Q
A
A
A
I
Q
Q
Q
Q
Q
Q



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Intensity (CPS)
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S3-Jun 2005
I
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C
Q
K
A
Q
Mu
Q
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44
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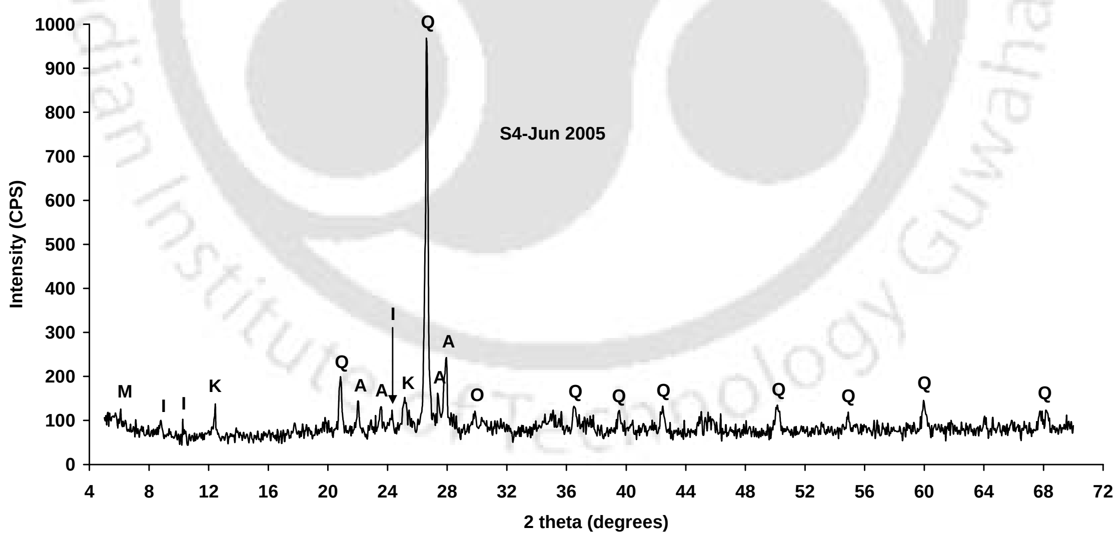
52
56
60
64
68
72
2 theta (degrees)



1000
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Intensity (CPS)
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S4-Jun 2005
M
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Q
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I
K
A
A
O
Q
Q
Q
Q
Q
Q
Q
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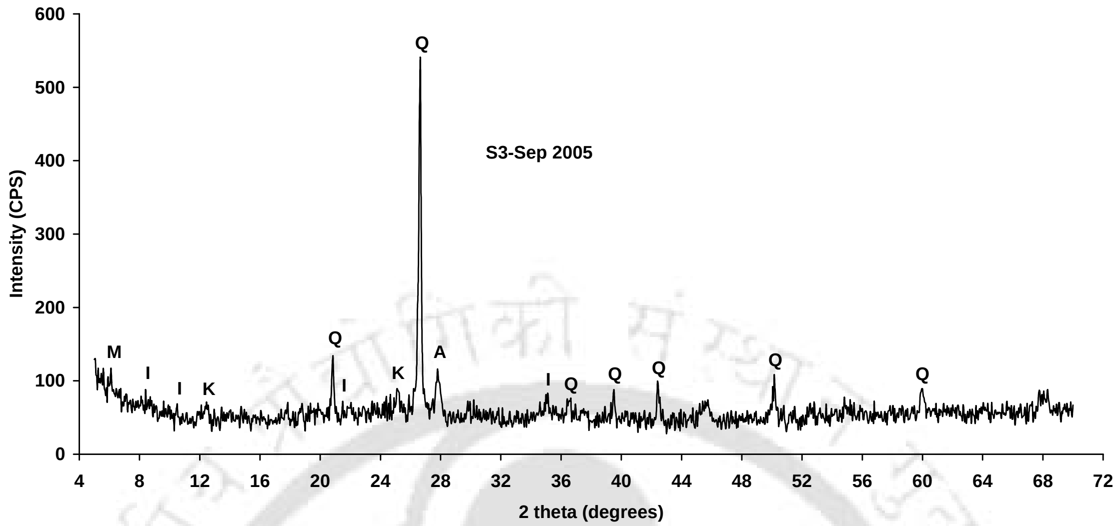
72
2 theta (degrees)


600
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Intensity (CPS)
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S3-Sep 2005
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Q
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Q
Q
Q
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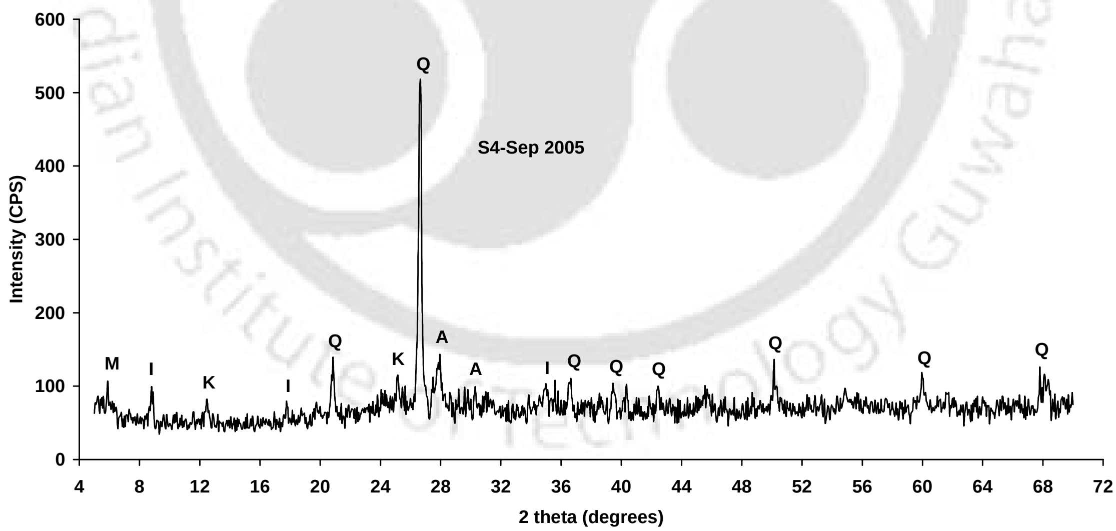
68
72
2 theta (degrees)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Intensity (CPS)
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S4-Sep 2005
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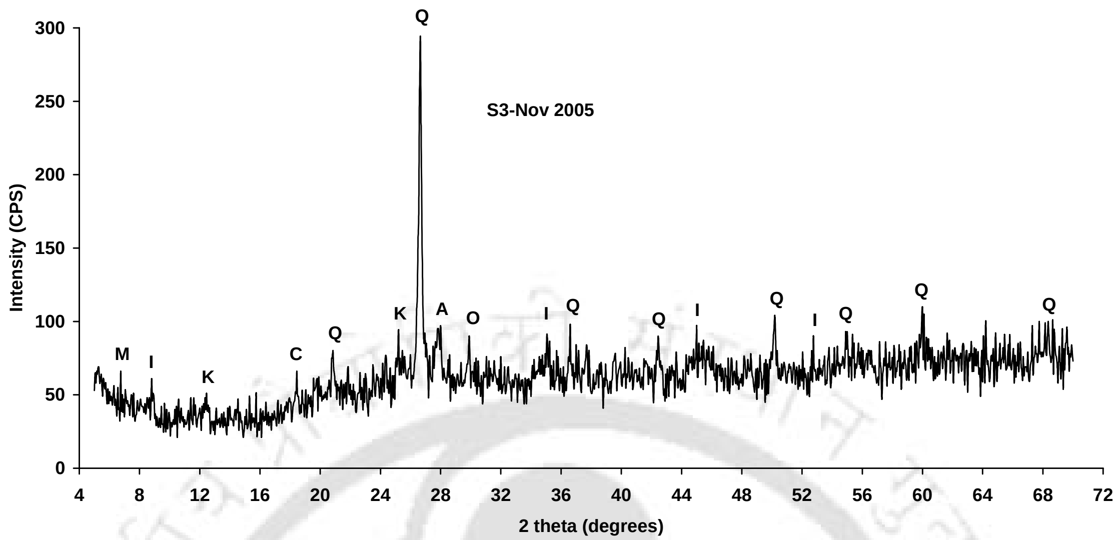
2 theta (degrees)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Intensity (CPS)
2 theta (degrees)
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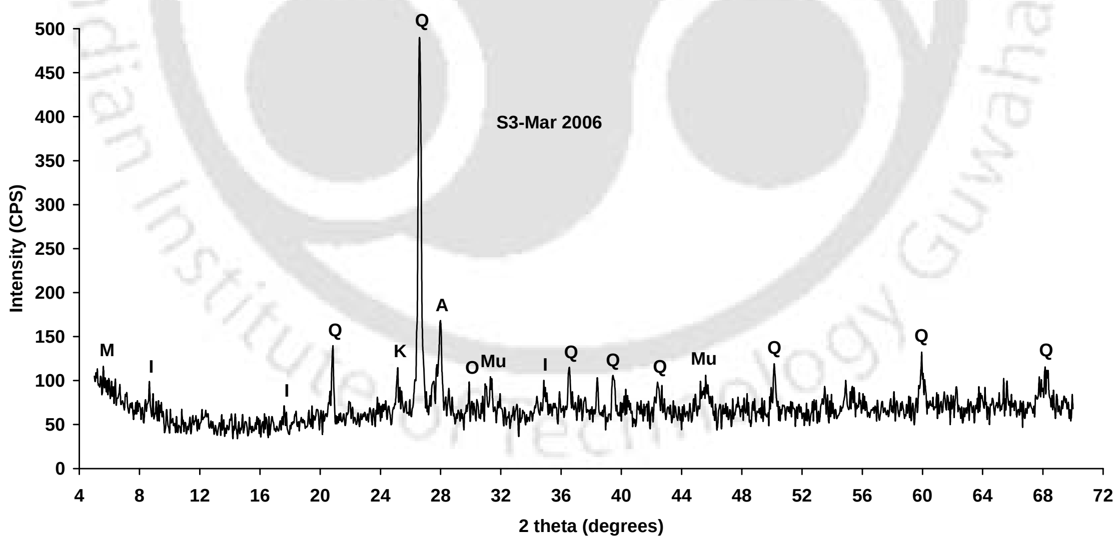
Q
I
Q
Q
Q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2 theta (degrees)
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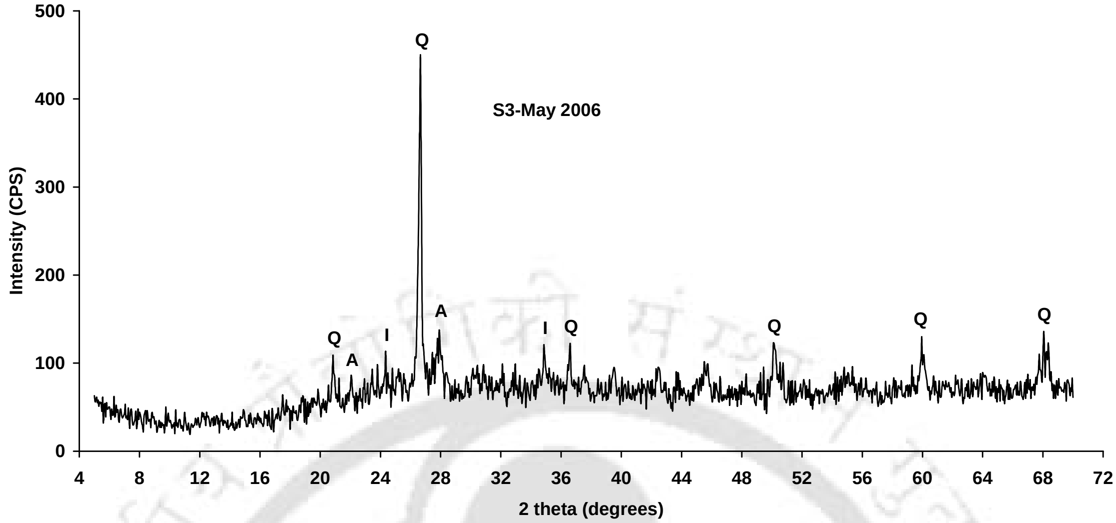
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Intensity (CPS)
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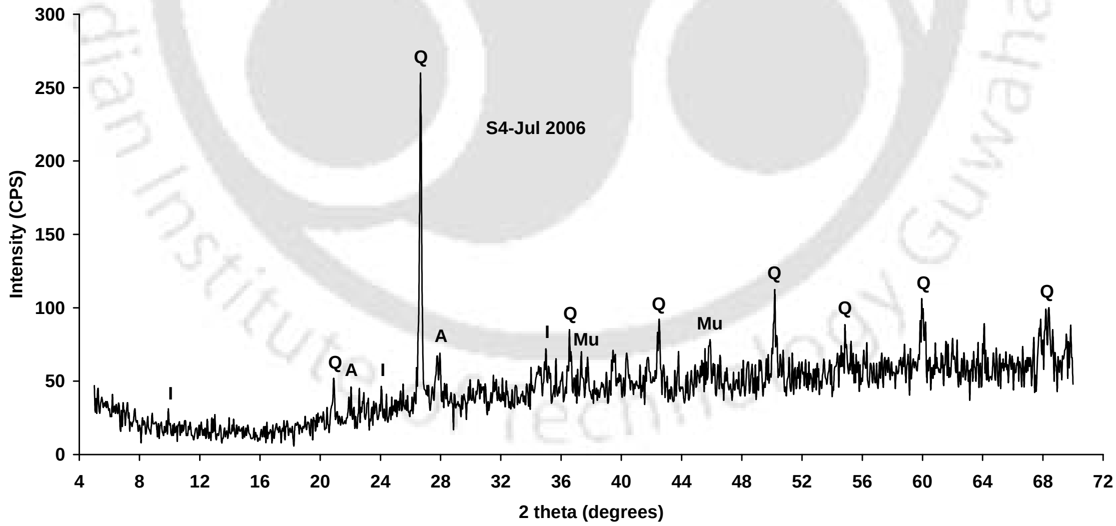
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Intensity (CPS)
2 theta (degrees)
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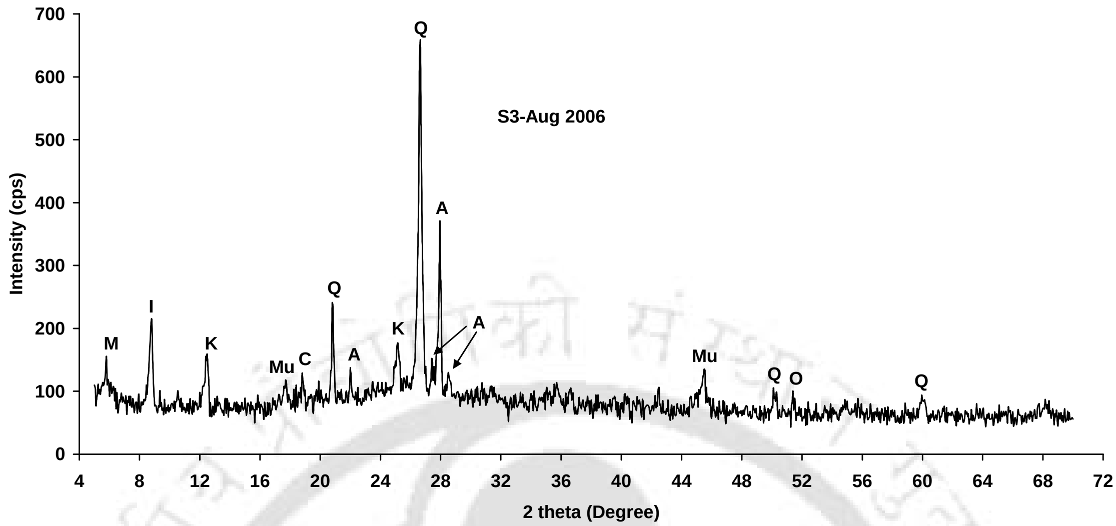

S3-Aug 2006
Intensity (cps)
2 theta (Degree)
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Mu
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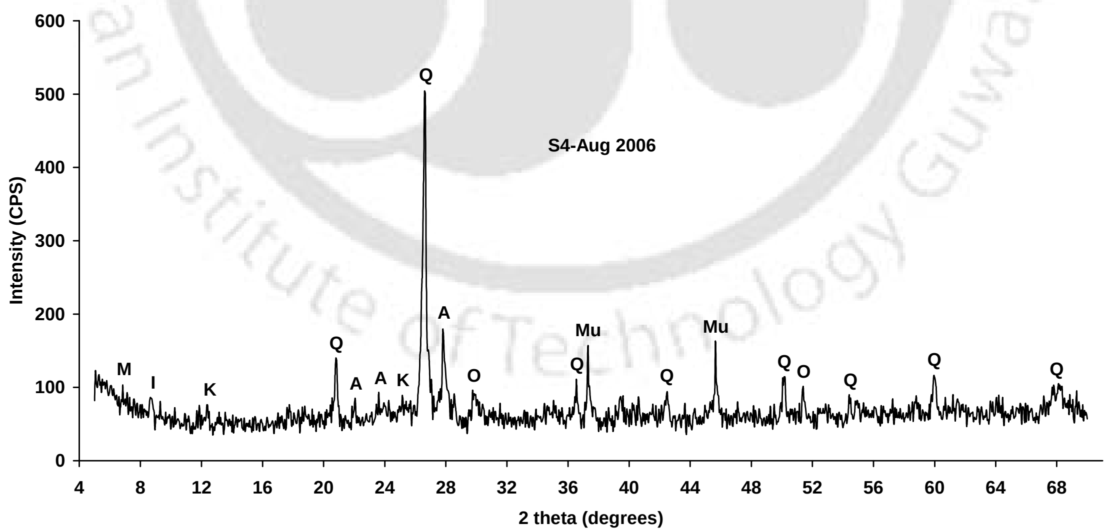
Q



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Intensity (CPS)
2 theta (degrees)
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Mu
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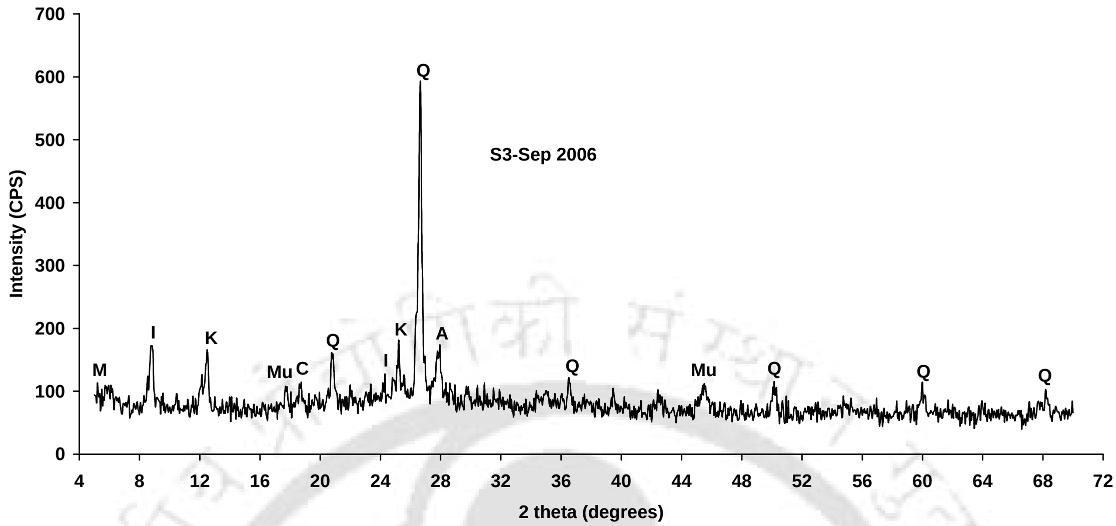
Q
O
Q
Q
Q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Intensity (CPS)
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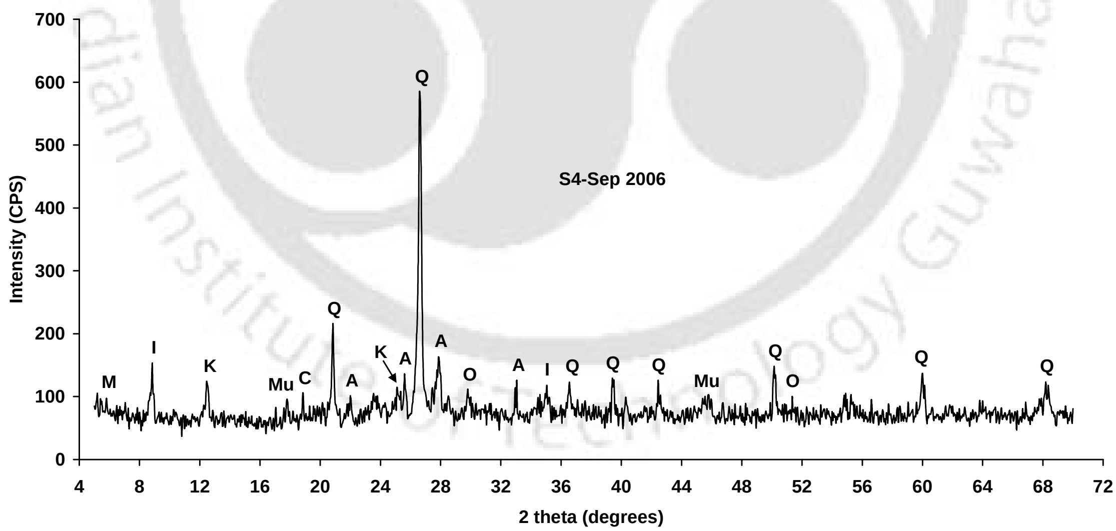
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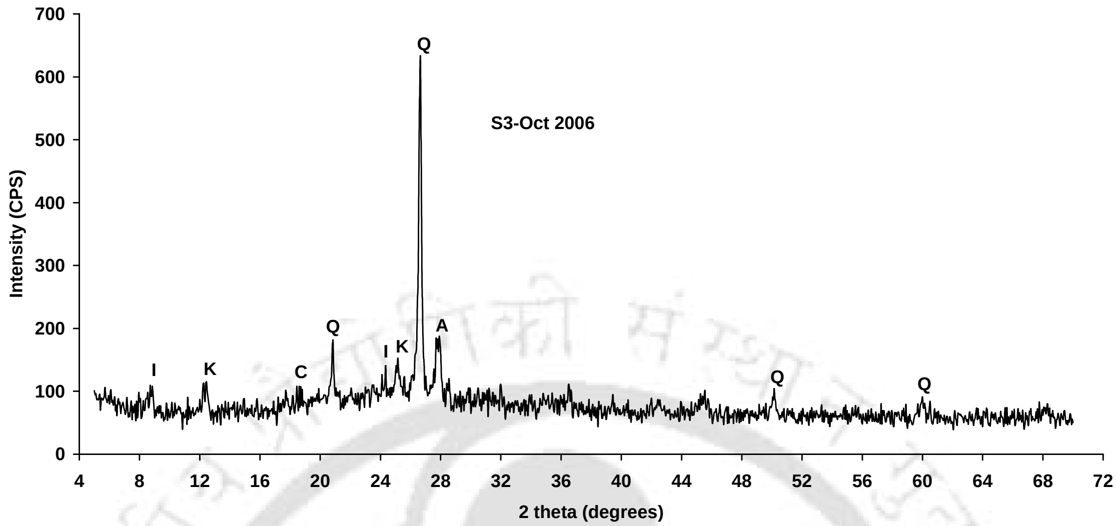
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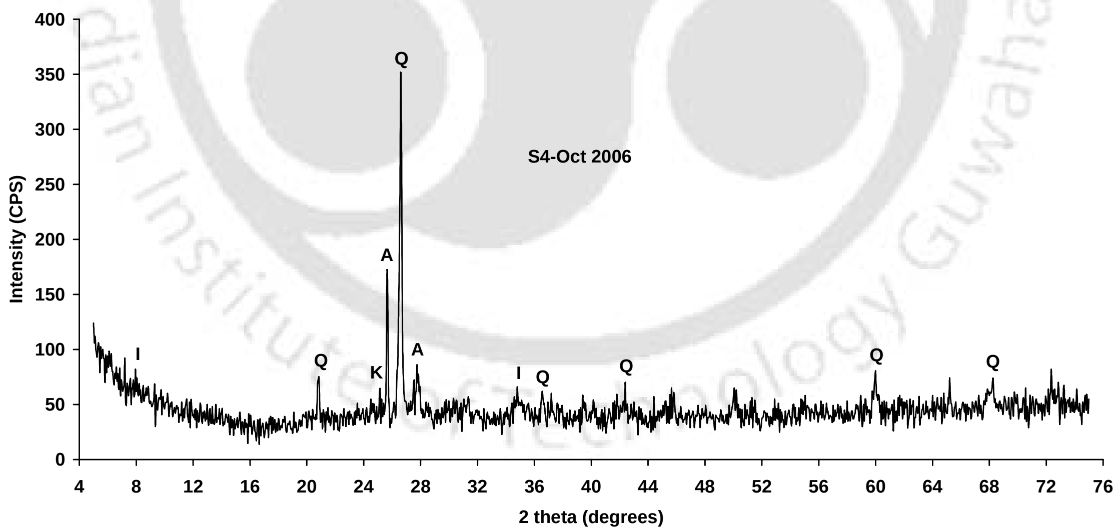
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Intensity (CPS)
2 theta (degrees)
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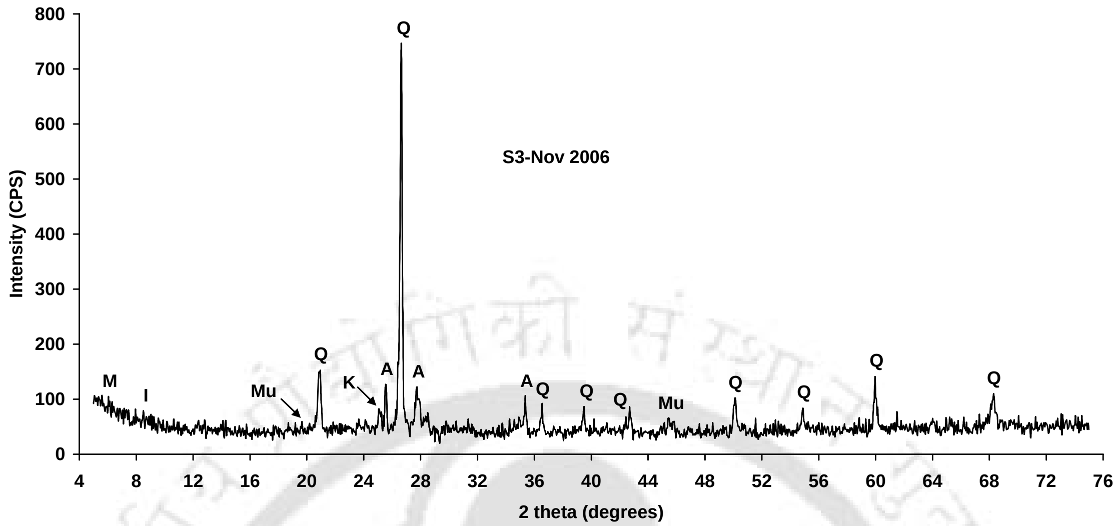
Intensity (CPS)
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S3-Nov 2006
Q
M
I
Mu
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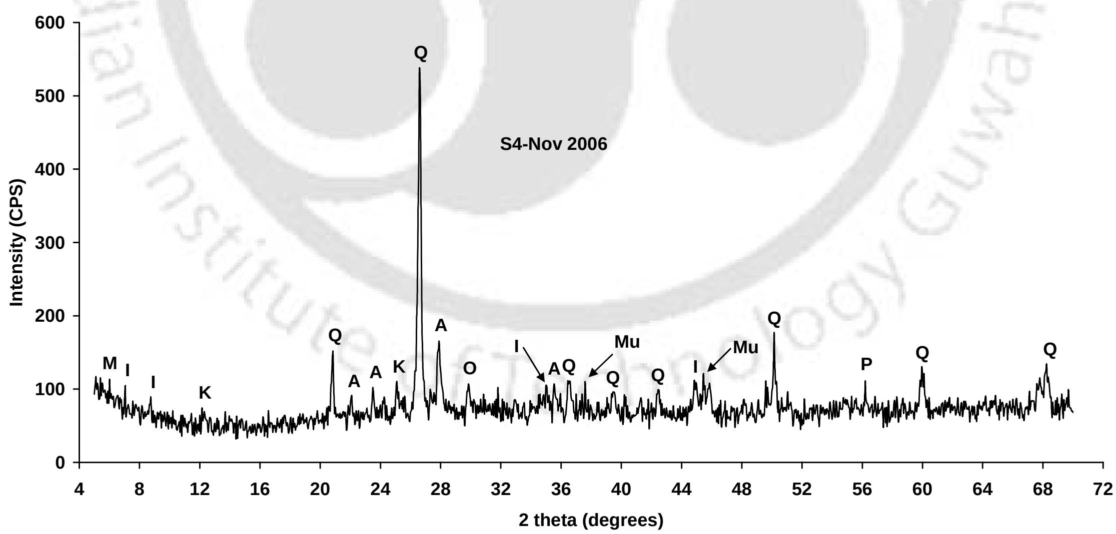
A
Mu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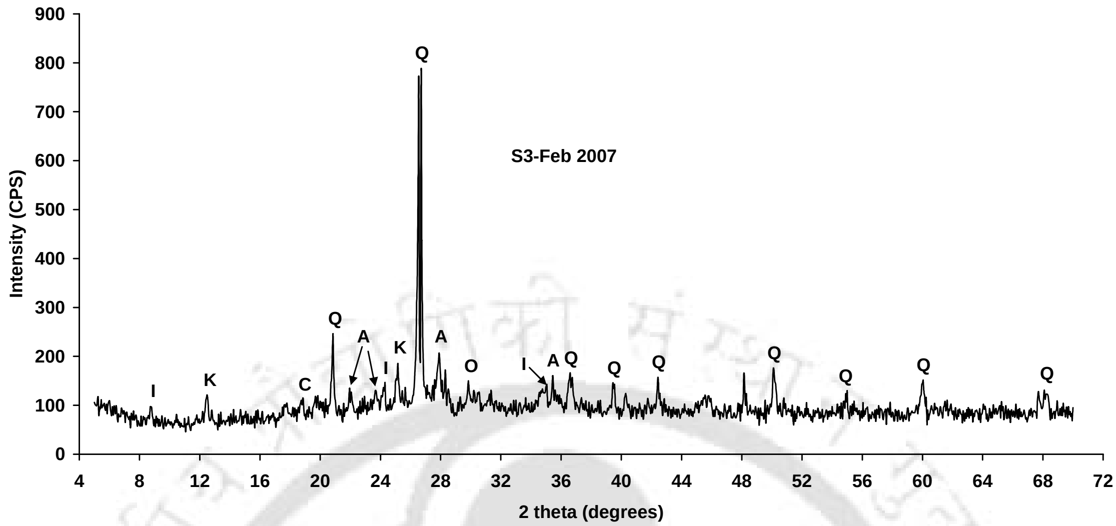
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Intensity (CPS)
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52
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68
72
2 theta (degrees)
S3-Feb 2007
Q
A
K
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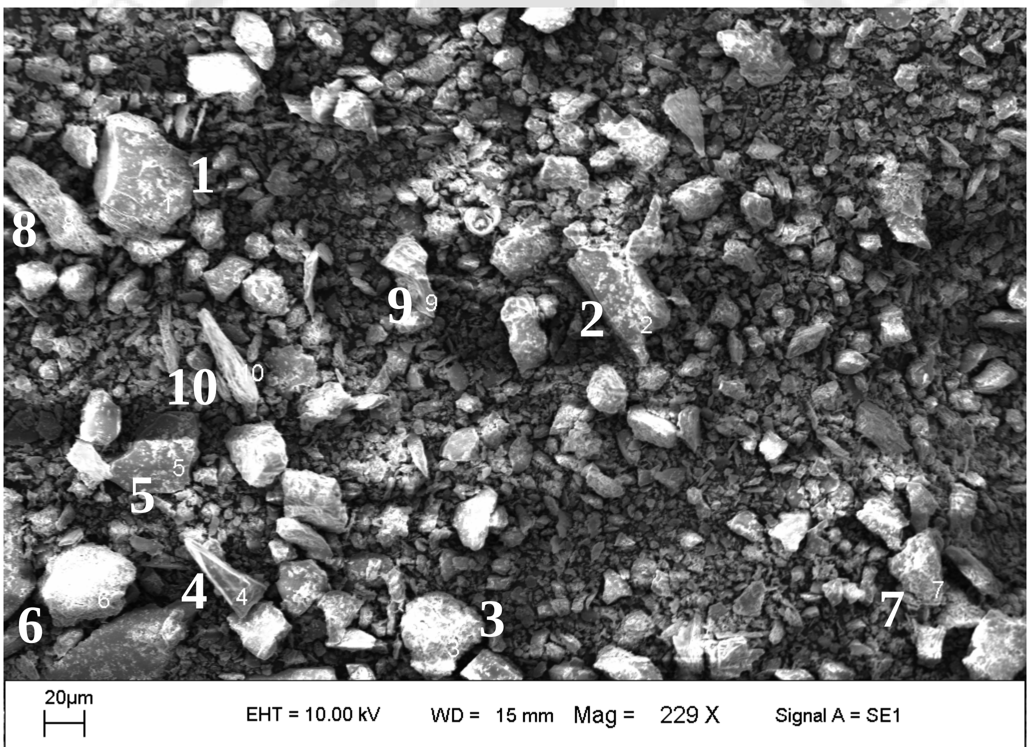
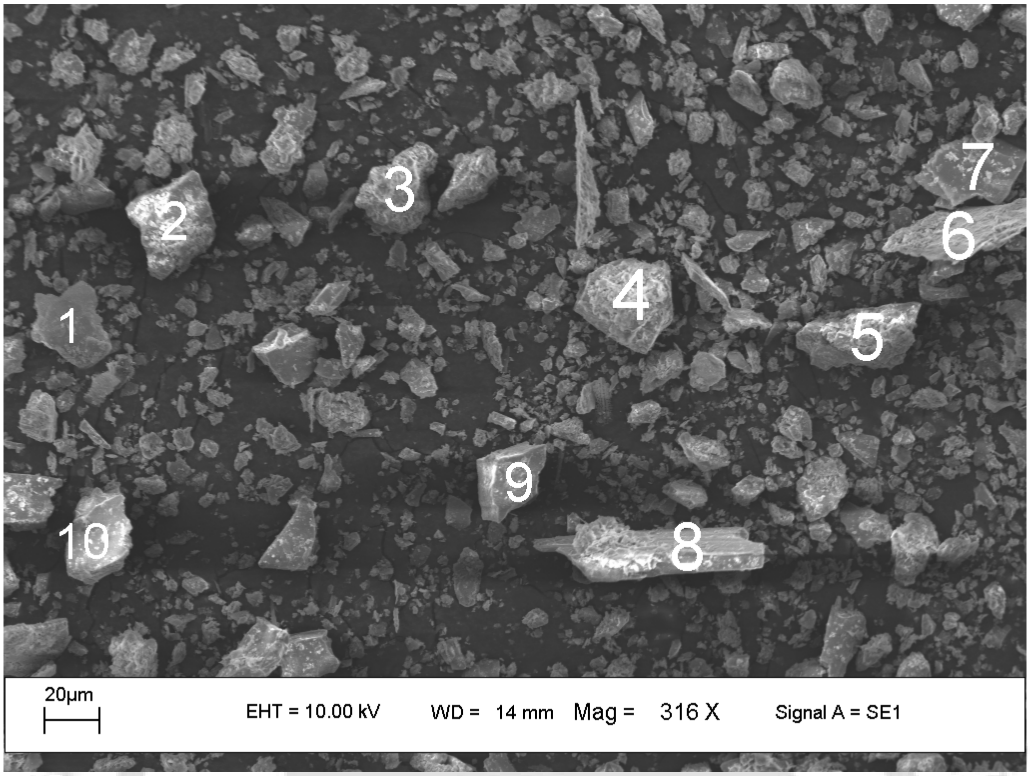
<u>Scanning Electron Micrographs</u>

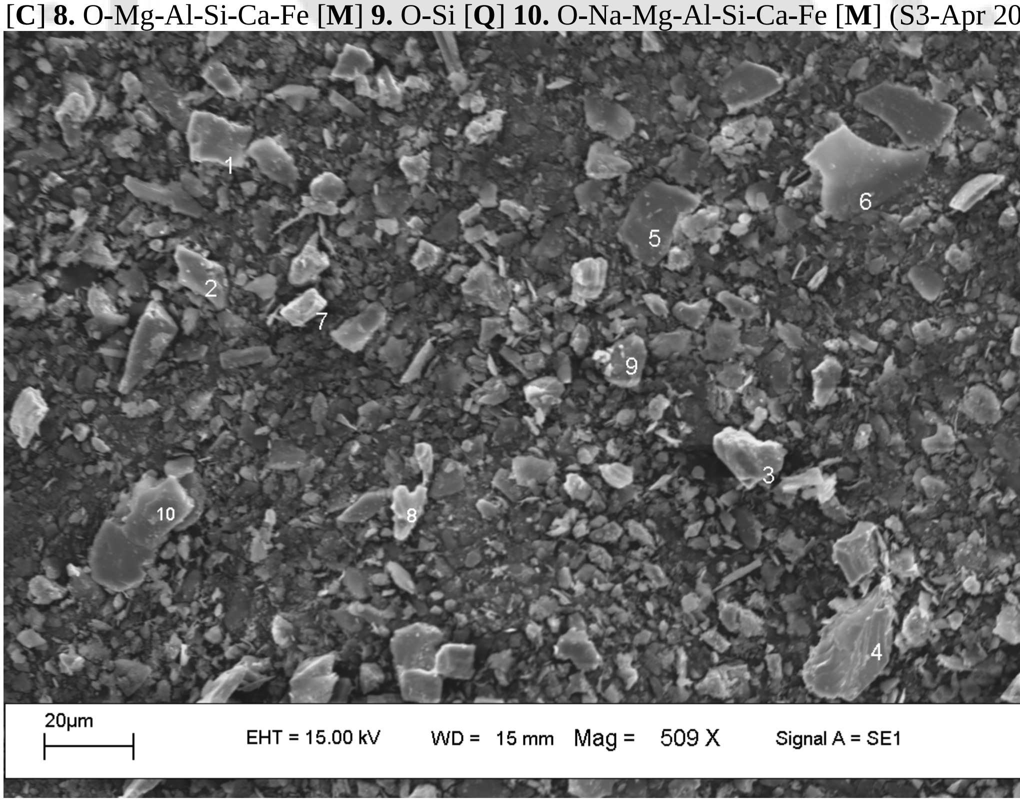
(Sample names have been given at the end of the caption of each figure. Here, "S" indicates TWLSS sample and "B" indicates bed sediment sample.)



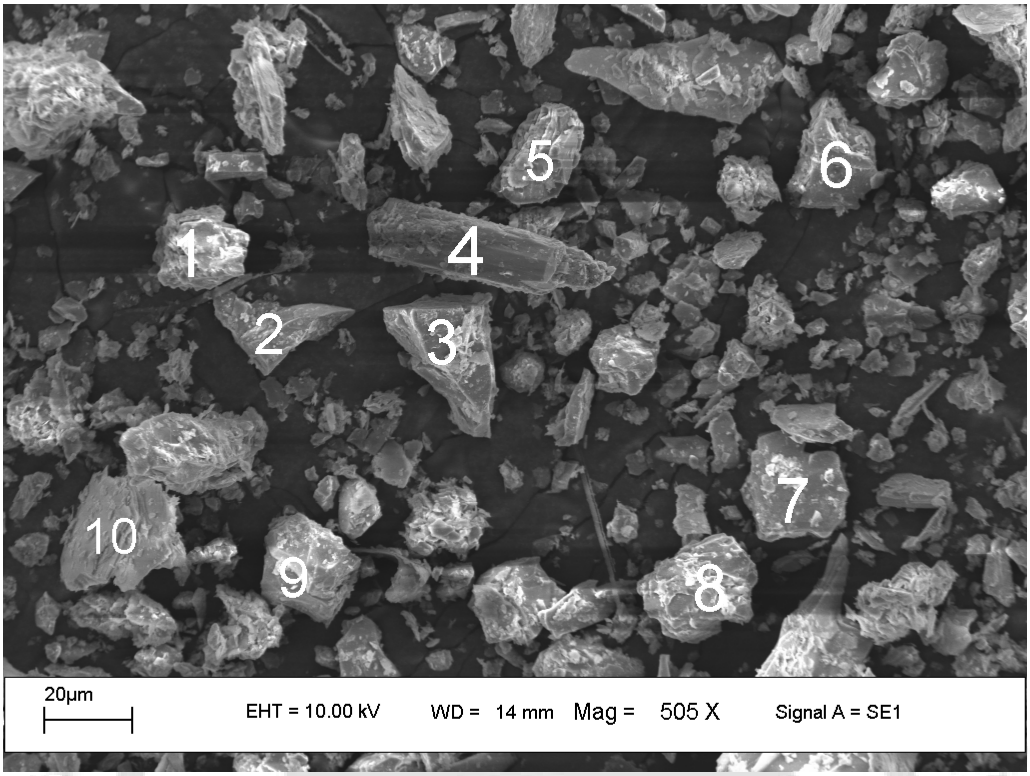
1. O-Mg-Al-Si-K-Fe [**I**] **2.** O-Mg-Al-Si-K [**I**] **3, 6 & 9.** O-Na-Al-Si [**A**] **4.** O-Si [**Q**] **5.** O-Mg-Al-Si-Fe [**C**] **7.** O-Al-Si-Ca-Fe [**M**] **8 & 10.** O-Mg-Al-Si [**C**] (S3-Mar 2006)



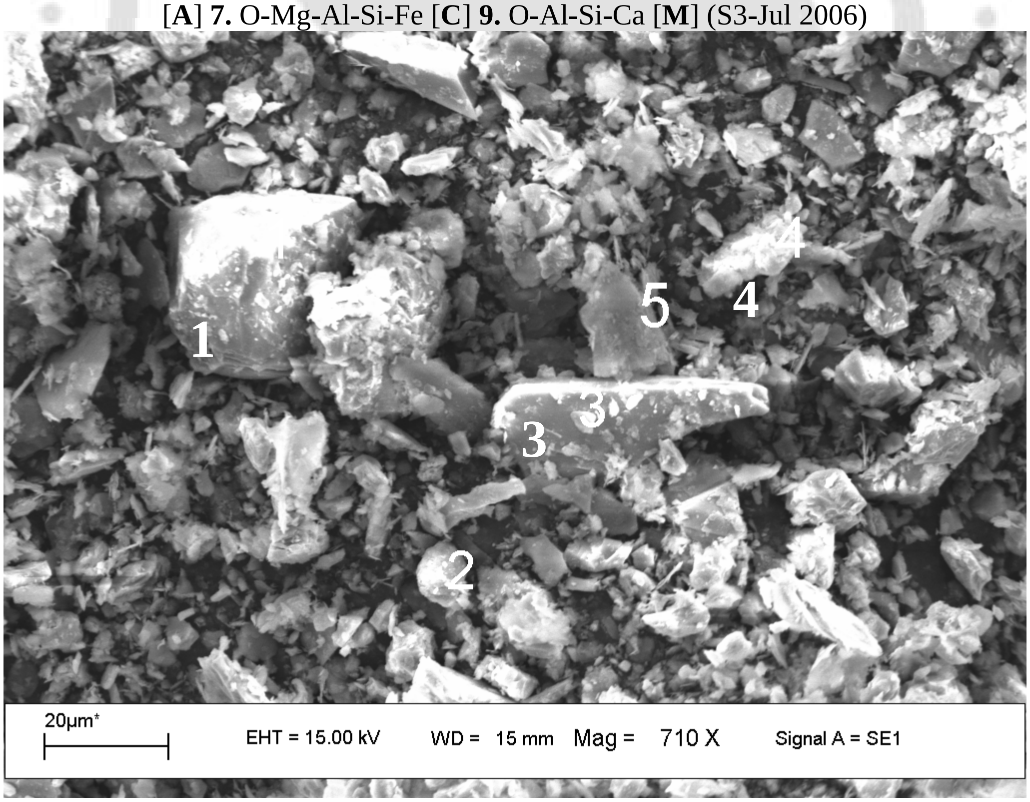
1 & 7. O-Al-Si-K [**O**] **2.** O-Na-Mg-Al-Si-Fe [**M**] **3.** Si **4 & 5.** O-Mg-Al-Si-K [**I**] **6.** O-Mg-Al-Si-Fe [**C**] **8.** O-Mg-Al-Si-Ca-Fe [**M**] **9.** O-Si [**Q**] **10.** O-Na-Mg-Al-Si-Ca-Fe [**M**] (S3-Apr 2006)



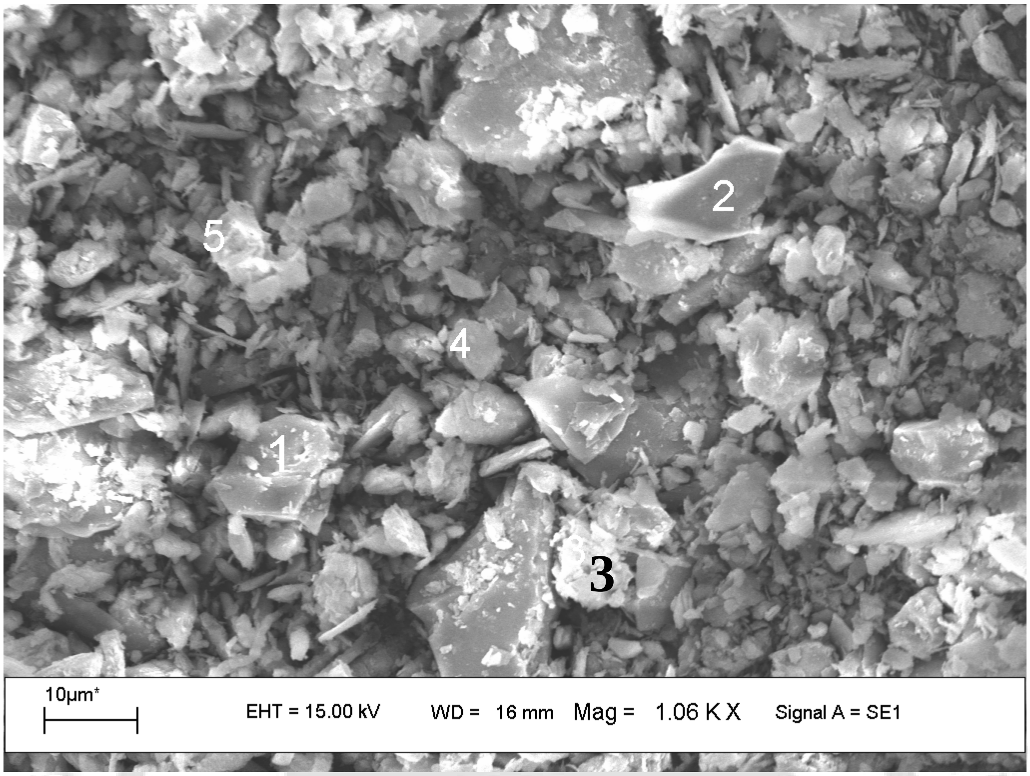
1. O-Na-Al-Si-Ca [**M**] **2.** O-Na-Al-Si-K-Fe [**M**] **3 & 5.** O-Al-Si-K [**O**] **4.** O-Al-Si-Fe [**C**] **6 & 7.** O-Mg-Al-Si-K-Fe [**I**] **8.** O-Al-Si [**K**] **9.** O-Mg-Al-Si-Fe [**C**] **10.** O-Al-Si-K-Fe (S3-May 2006)



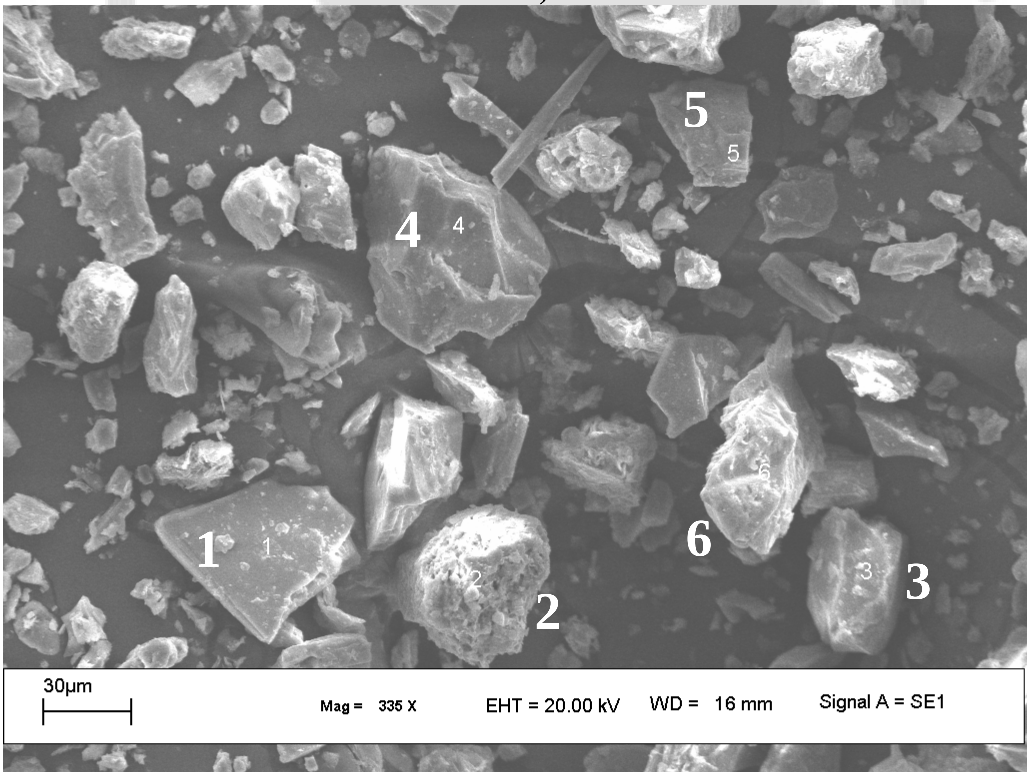
1 & 10. O-Al-Si-K [**Mu**] **2, 6 & 8.** O-Si [**Q**] **3.** O-Al-Si [**K**] **4.** O-Mg-Al-Si [**C**] **5.** O-Na-Al-Si [**A**] **7.** O-Mg-Al-Si-Fe [**C**] **9.** O-Al-Si-Ca [**M**] (S3-Jul 2006)



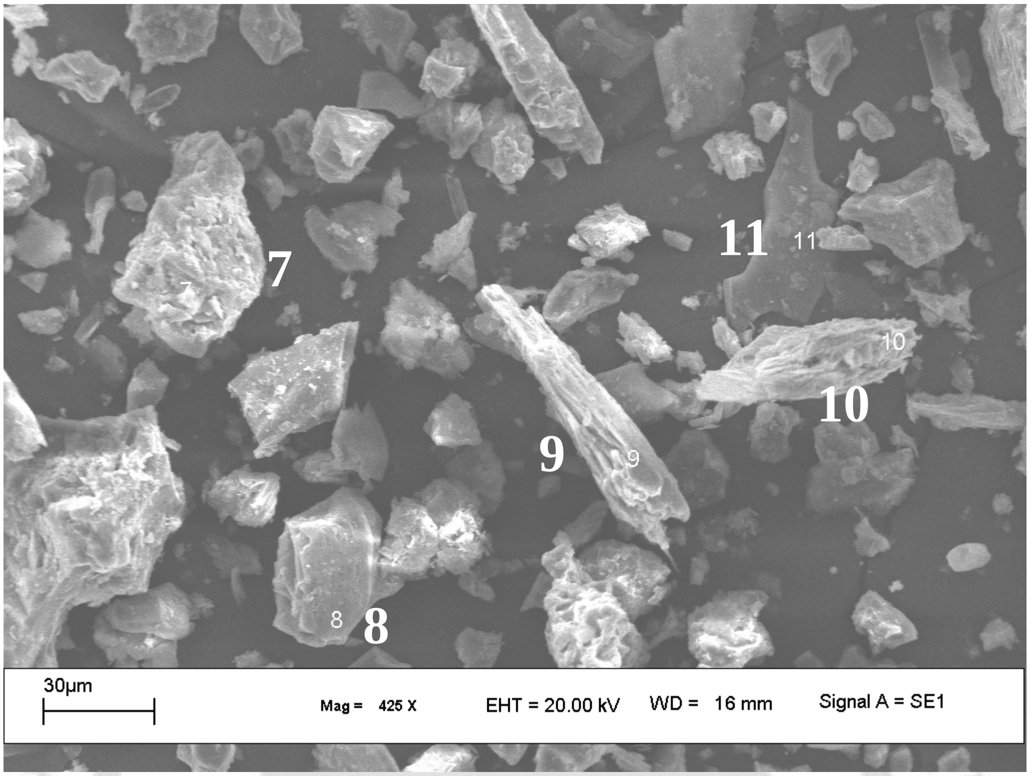
1. O-Si [**Q**] **2.** O-Mg-Al-Si-Fe [**C**] **3.** O-Mg-Al-Si-K-Fe [**I**] **4.** O-Al-Si-Fe [**C**] **5.** O-Al-Si [**K**] (S3-Sep 2006)



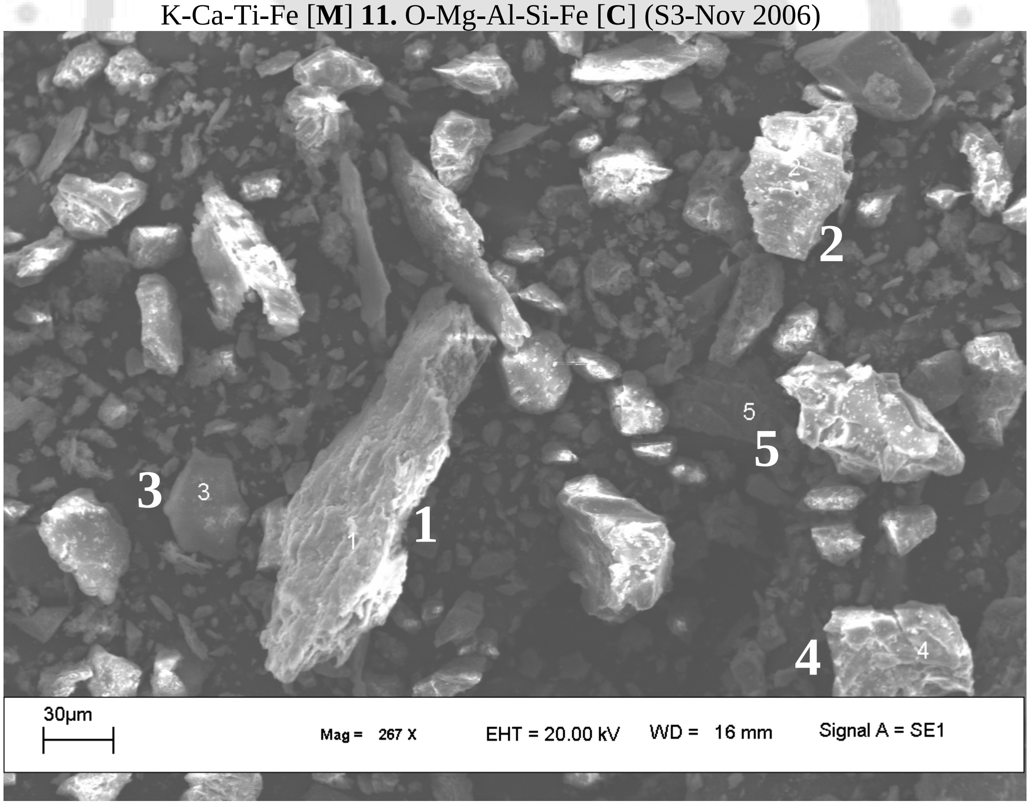
1. O-Al-Si-K-Ca **2.** O-Al-Si-K [**O**] **3.** O-Al-Si-K-Fe [**I**] **4 & 5.** O-Mg-Al-Si-K-Fe [**I**] (S3-Oct 2006)



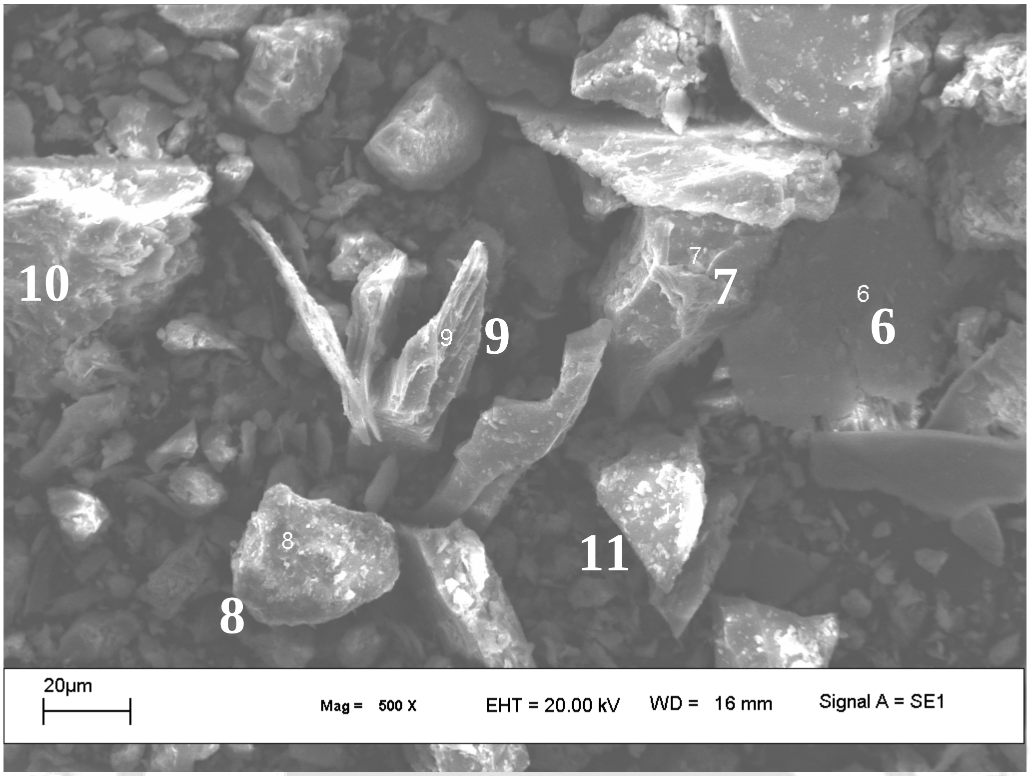
1. Na-Al-Si-K-Fe [**M**] **2.** Na-Al-Si-O [**A**] **3.** Si-O [**Q**] **4.** Fe-Si-O [**C**] **5.** Si-O [**Q**] **6.** O-Al-Si-K-Fe [**I**] (S3-Nov 2006)



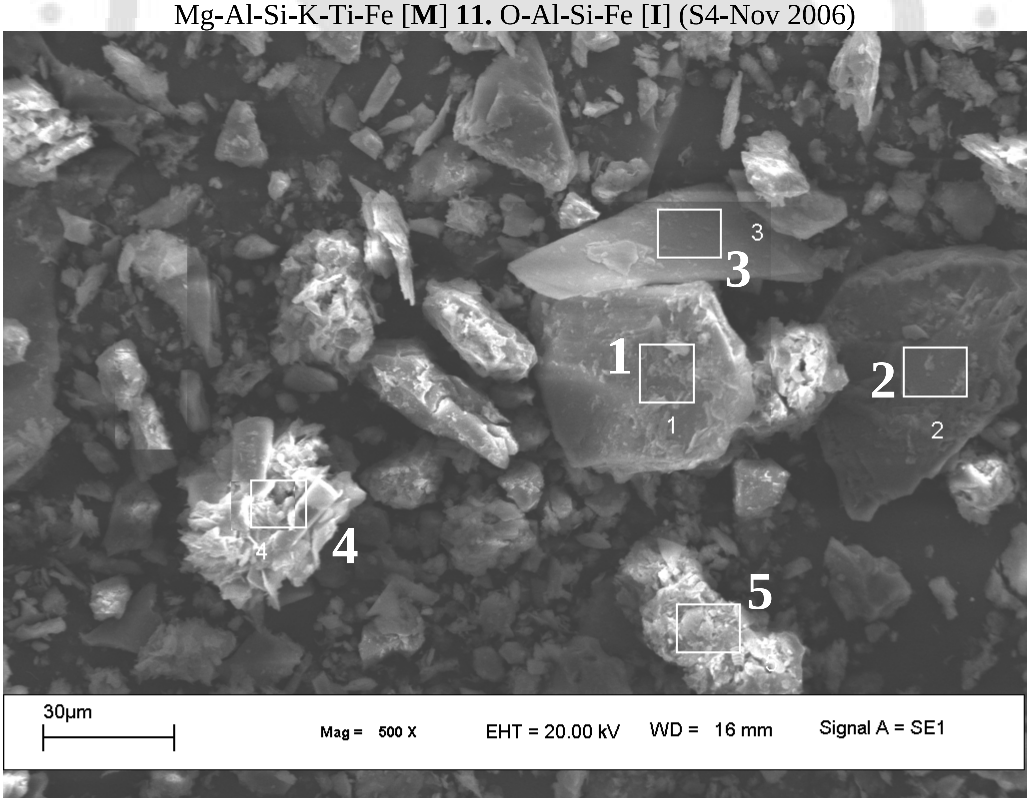
7. O-Na-Mg-Al-Si-Ca-Fe [**M**] **8**. O-Na-Al-Si-Ca [**M**] **9.** O-Mg-Si-Al-Ca-Fe [**M**] **10.** O-Mg-Al-Si-K-Ca-Ti-Fe [**M**] **11.** O-Mg-Al-Si-Fe [**C**] (S3-Nov 2006)



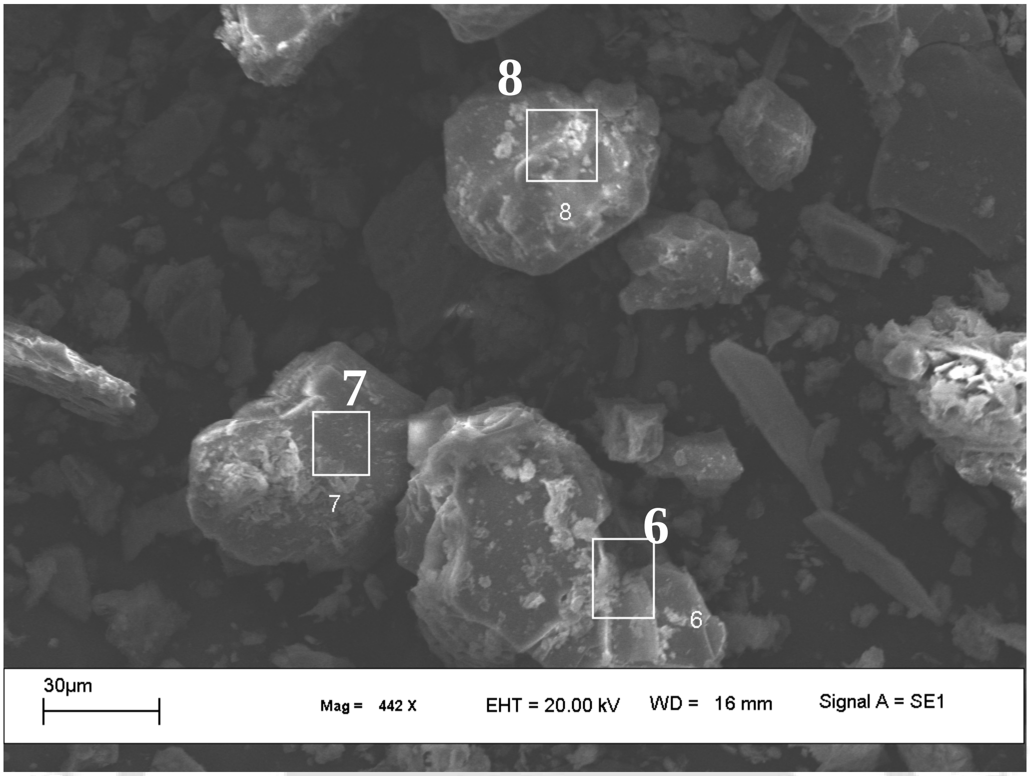
1. O-Na-Mg-Al-Si-K-Ca-Fe [**M**] **2.** O-Na-Al-Si-K-Fe [**M**] **3.** O-Mg-Al-Si-K-Fe [**I**] **4.** O-Na-Al-Si-Ca-Fe [**M**] **5.** O-Na-Al-Si-Ca [**M**] (S4-Nov 2006)



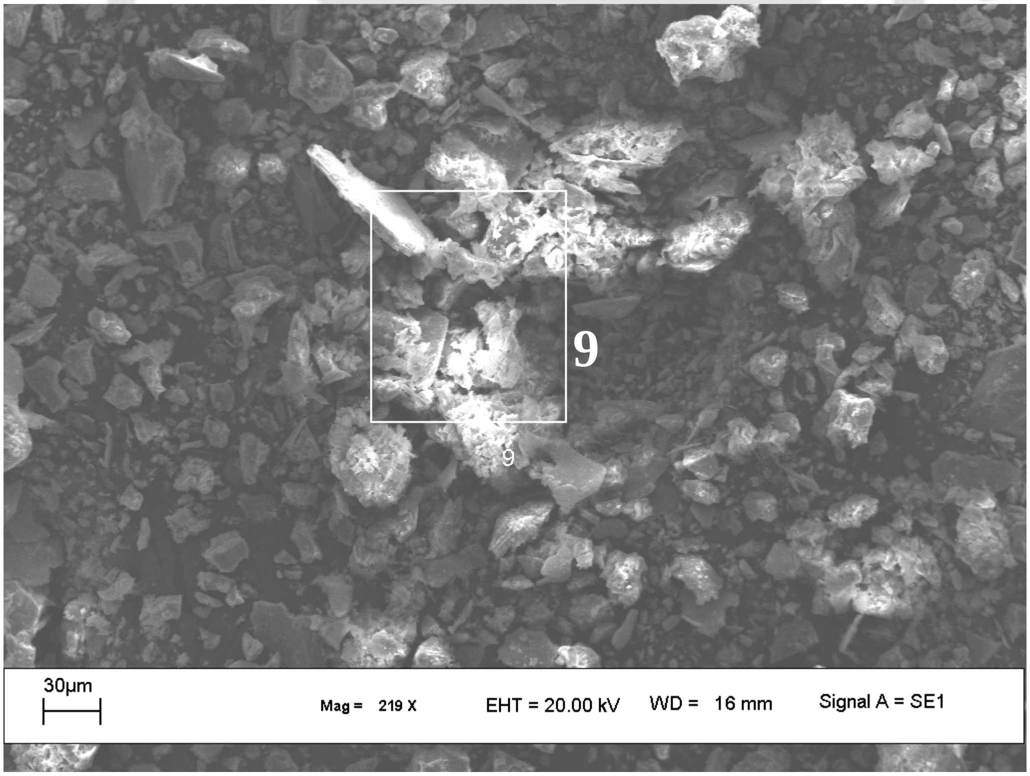
6. O-Mg-Al-Si-K-Ti-Fe [**I**] **7.** O-Al-Si-K [**O**] **8 & 9.** O-Na-Mg-Al-Si-K-Ca-Fe [**M**] **10.** O-Na-Mg-Al-Si-K-Ti-Fe [**M**] **11.** O-Al-Si-Fe [**I**] (S4-Nov 2006)



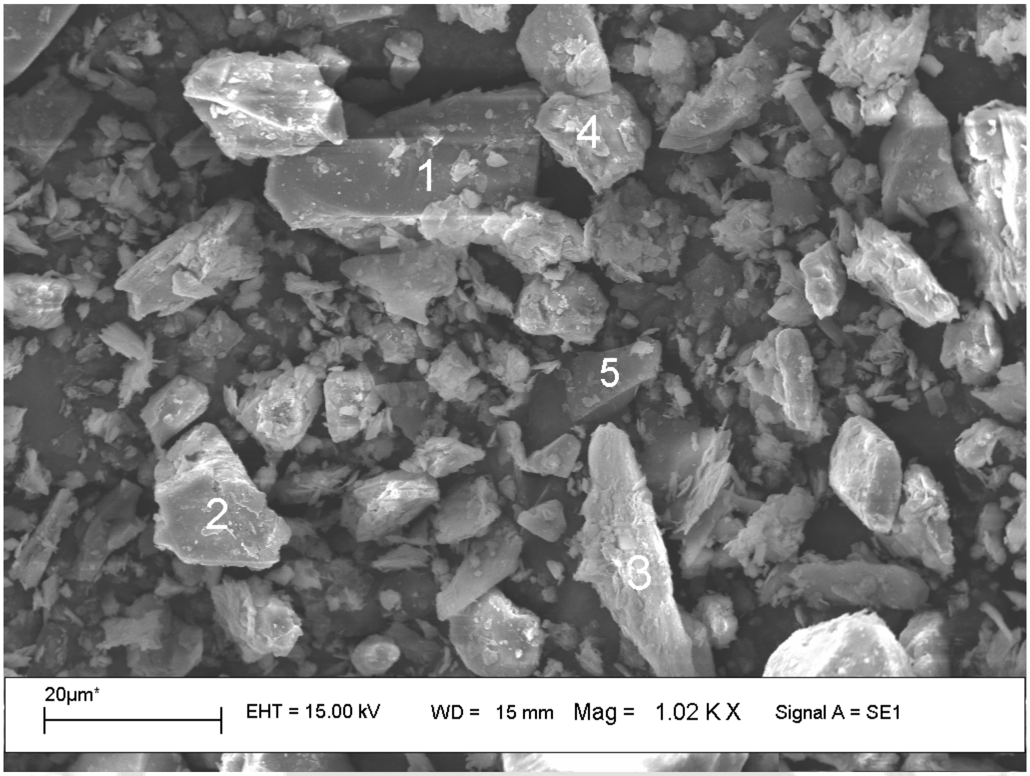
1. O-Mg-Al-Si-K-Ca-Ti-Fe-Cu [**M**] **2.** O-Mg-Si-Ca-Fe [**M**] **3.** O-Mg-Al-Si-K-Ti-Fe-Cu [**I**] **4.** O-Na-Mg-Al-Si-K-Ca-Ti-Fe-Cu [**M**] **5.** O-Mg-Al-Si-K-Ca-Ti-Fe-Cu [**M**] (S5-Nov 2006)



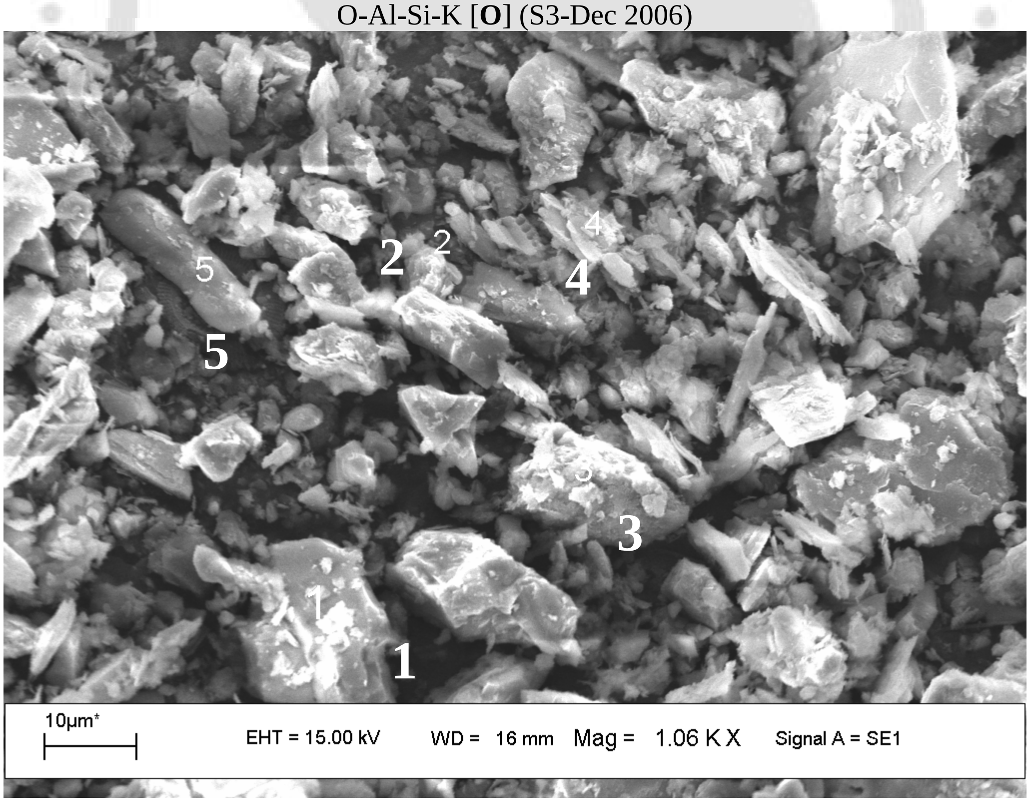
6. O-Mg-Al-Si-K-Fe-Cu [**I**] **7.** O-Al-Si-K-Ti-Fe-Cu [**I**] **8.** O-Na-Al-Si-Ca-Cu [**M**] (S5-Nov 2006)



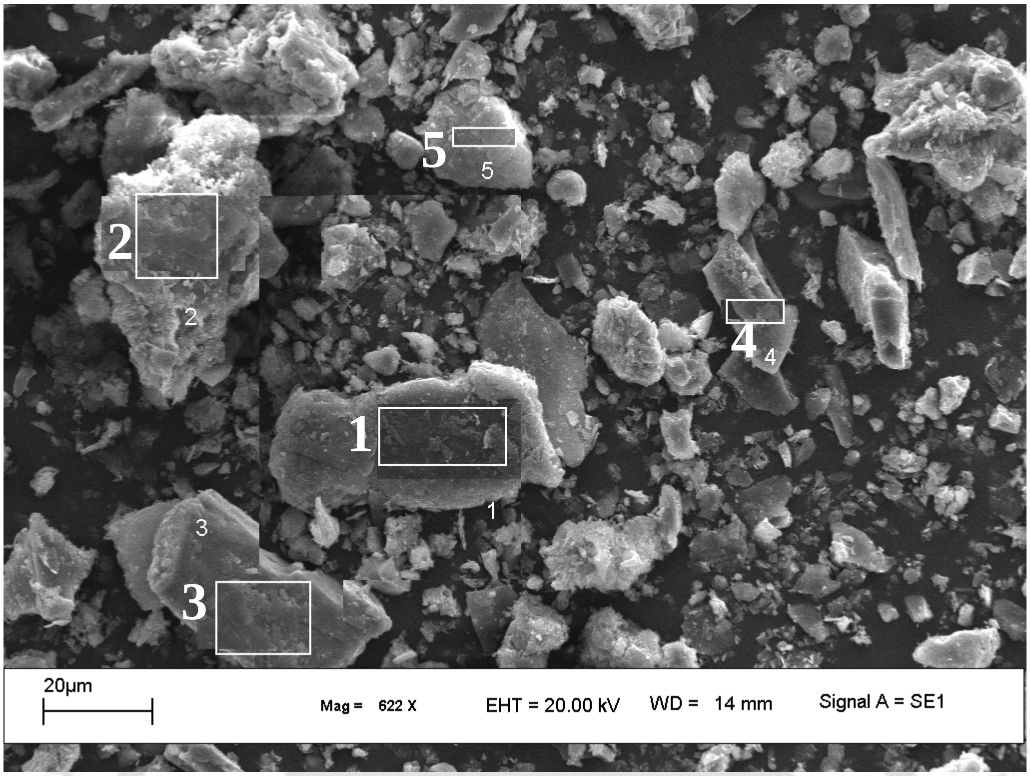
9. O-Mg-Al-Si-K-Fe-Cu [**I**] (S5-Nov 2006)



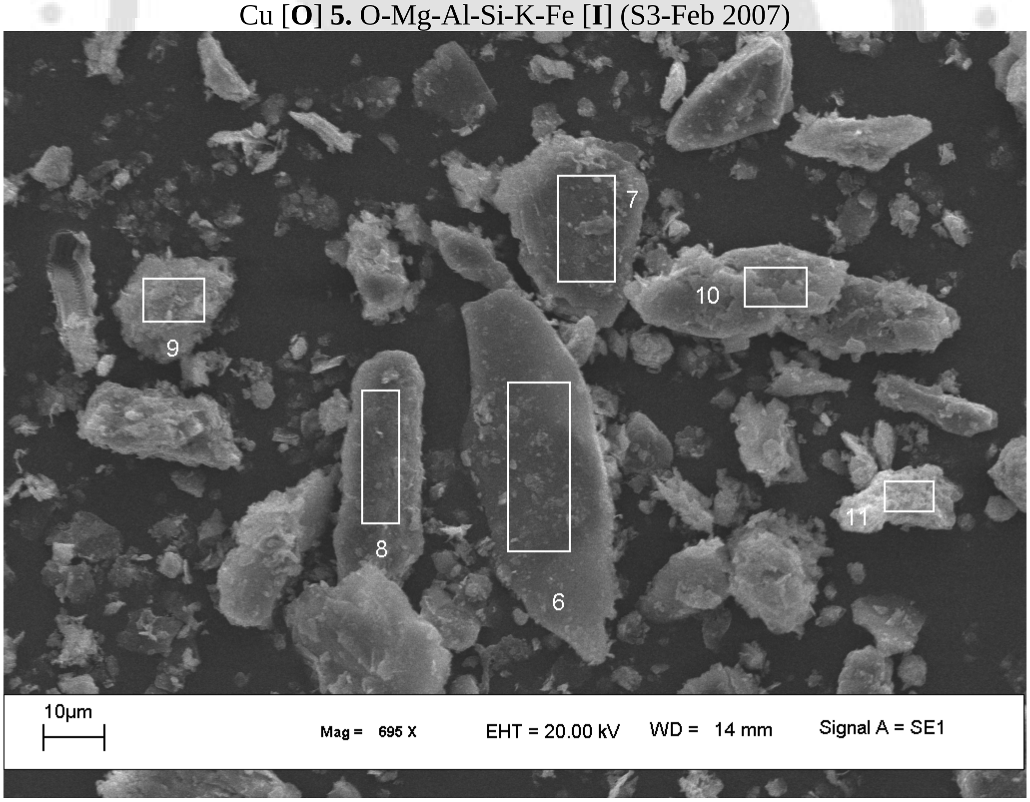
1. O-Mg-Al-Si-Ca-Fe [**M**] **2.** O-Na-Al-Si-Ca [**M**] **3.** O-Al-Si-K-Fe [**I**] **4.** O-Na-Al-Si-Ca [**M**] **5.** O-Al-Si-K [**O**] (S3-Dec 2006)



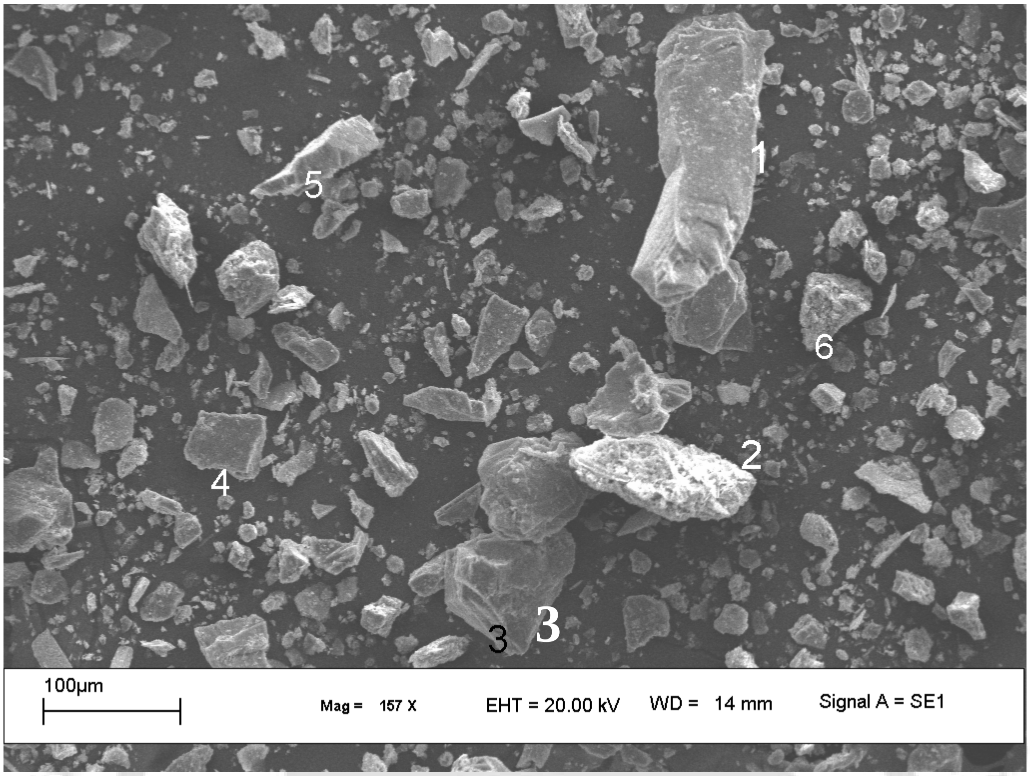
1. O-Mg-Al-Si-Ca-Fe [**M**] **2 & 3.** O-Mg-Al-Si-Fe [**C**] **4.** O-Mg-Al-Si-K-Fe [**I**] **5.** O-Mg-Al-Si-Fe [**C**] (S3-Jan 2007)



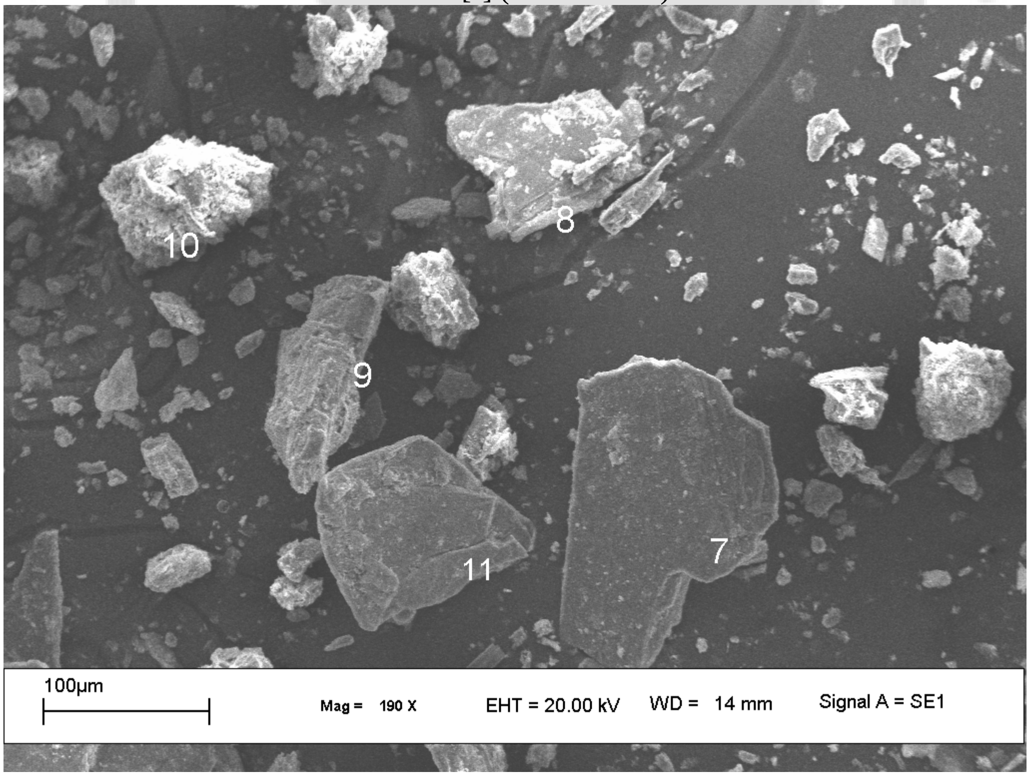
1. O-Mg-Al-Si-Ca-Fe-Cu [**M**] **2.** O-Mg-Al-Si-K-Ca-Fe [**M**] **3.** O-Al-Si-Ca-Fe [**M**] **4.** O-Al-Si-K-Cu [**O**] **5.** O-Mg-Al-Si-K-Fe [**I**] (S3-Feb 2007)



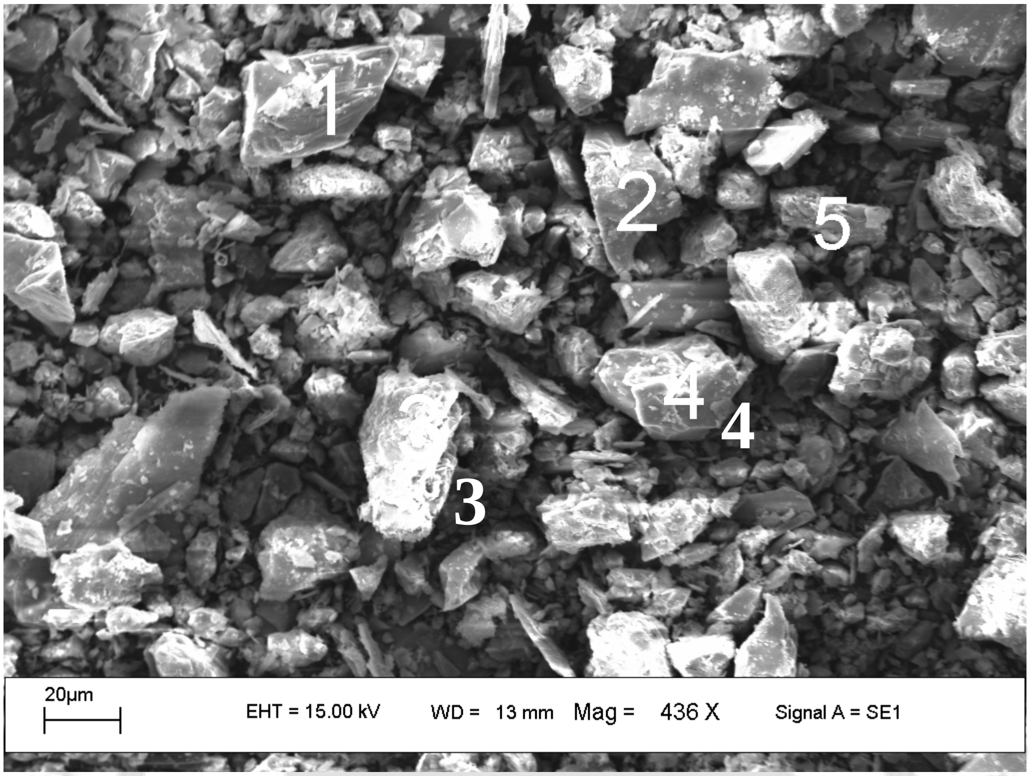
6. O-Mg-Al-Si-K-Fe-Cu [**I**] **7.** O-Mg-Al-Si-Fe-Cu [**C**] **8.** O-Si [**Q**] **9.** O-Mg-Al-Si-K-Fe-Cu [**I**] **10.** O-Al-Si-K-Ca-Fe [**M**] **11.** O-Al-Si-Ca-Fe [**M**] (S3-Feb 2007)



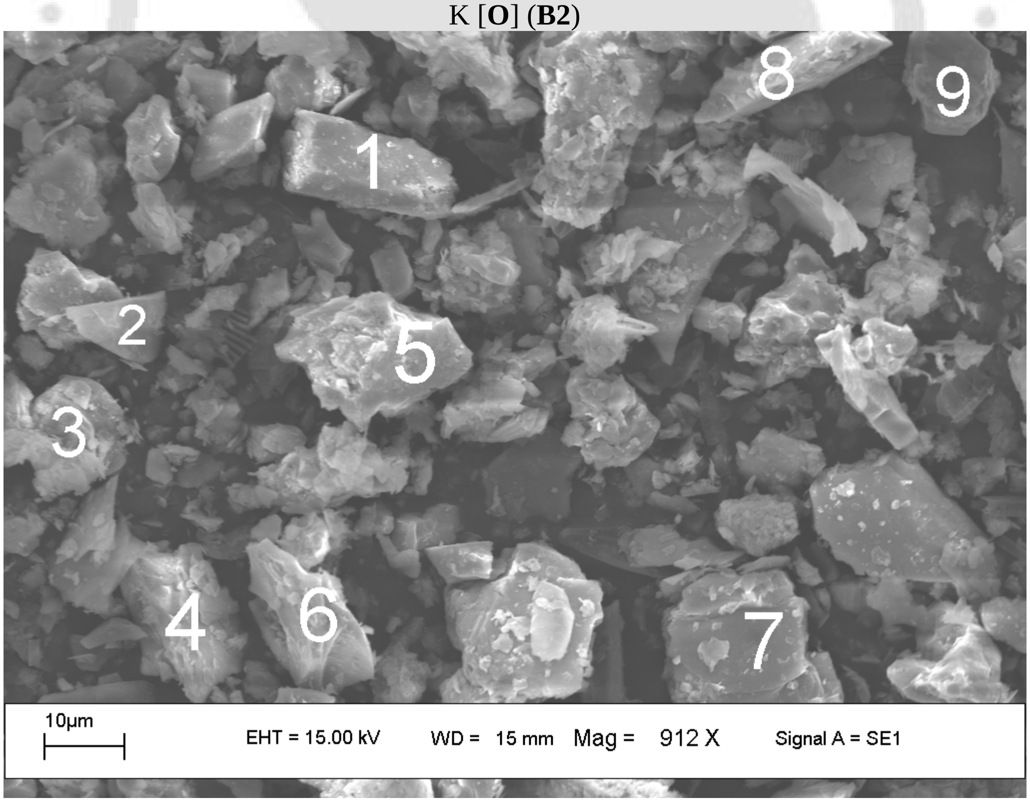
1. O- Si [**Q**] **2.** O- Al-Si-K-Ca- Fe [**M**] **3.** O-Mg-Al-Si [**B**] **4.** O- Al-Si-K [**O**] **5.** O-Si [**Q**] **6.** O-Al-Si-K-Fe [**I**] (S5-Feb 2007)



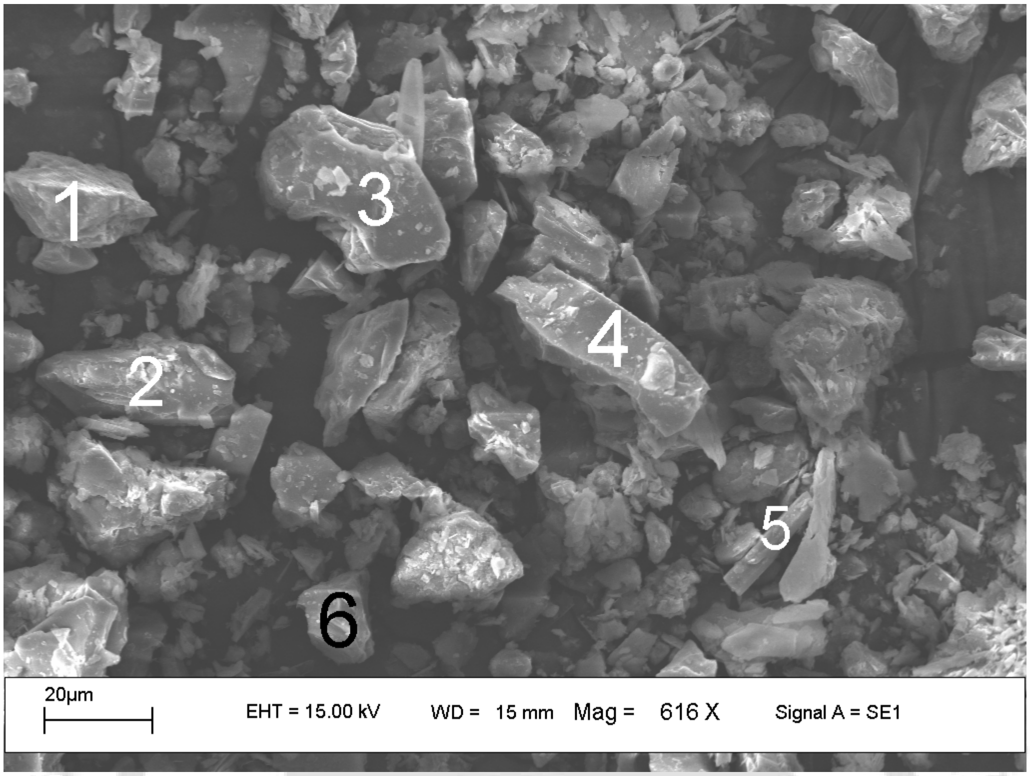
7. O-Al-Si-K [**O**] **8.** O-Mg-Al-Si-K-Ca-Fe [**M**] **9.** O-Mg-Al-Si-K [**I**] **10.** O-Al-Si-K-Fe [**I**] **11.** O-Si-Fe [**C**] (S5-Feb 2007)



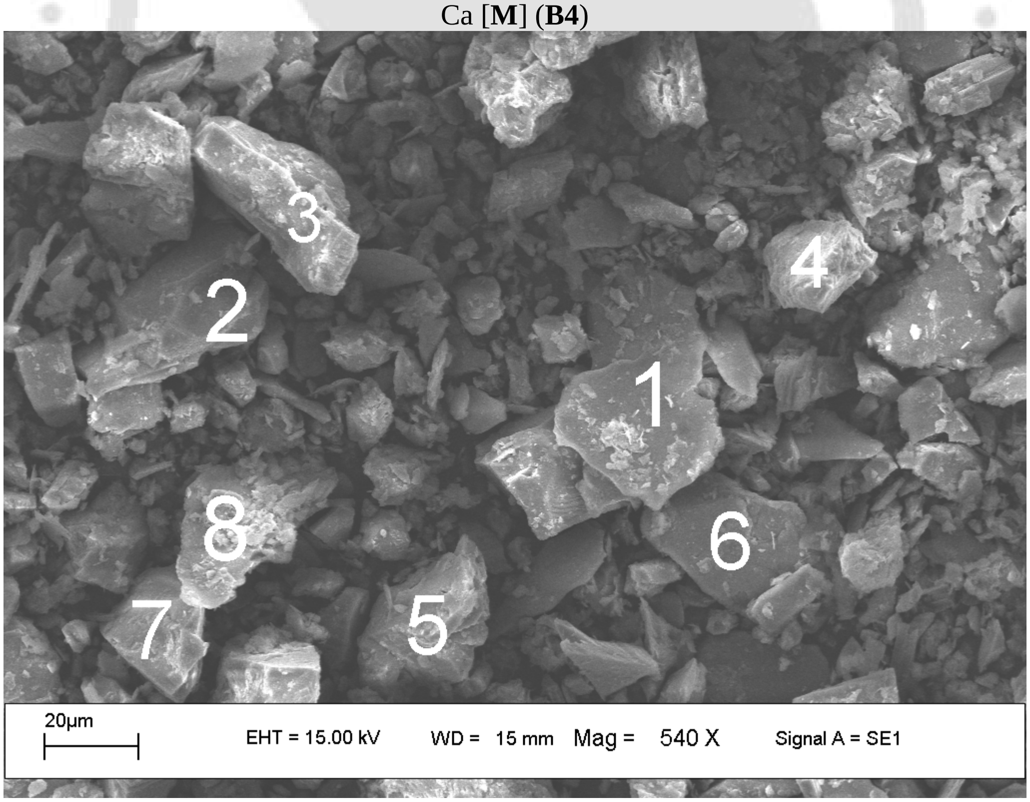
1. O-Al-Si-K-Ca-Fe [**M**] **2.** O-Na-Al-Si-Ca [**M**] **3.** O-Na-Al-Si-K-Fe [**M**] **4.** O-Si [**Q**] **5.** O-Al-Si-K [**O**] (**B2**)



1. O-Mg-Al-Si-Ca-Fe [**M**] **2, 3, 6 & 9.** O-Mg-Al-Si-Fe [**C**] **4.** O-Si [**Q**] **5.** O-Al-Si-K [**O**] **7.** O-Mg-Al-Si-K-Fe [**I**] **8.** O-Al-Si-K-Fe [**I**] (**B3**)



1 & 4. O-Si [**Q**] **2.** O-Al-Si [**K**] **3.** O-Mg-Al-Si-Fe [**C**] **5.** O-Mg-Al-Si-Ca-Fe [**M**] **6.** O-Na-Al-Si-Ca [**M**] (**B4**)



1 & 8. O-Mg-Al-Si-K-Fe [**I**] **2, 3 & 5.** O-Na-Al-Si-Ca [**M**] **4 & 7.** O-Al-Si [**K**] **6.** O-Mg-Al-Si-Ca-Ti-Fe [**I**] (**B5)**

Following Table shows dates of TWLSS sampling:

Sl No	Date of sampling	Number of samples	Locations
1	27-10-2004	3	S1, S3, S5
2	16-05-2005	5	S1, S2, S3, S4, S5
3	24-06-2005	5	S1, S2, S3, S4, S5
4	25-09-2005	2	S2, S3
5	27-11-2005	1	S3
6	04-03-2006	5	S1, S2, S3, S4, S5
7	08-04-2006	5	S1, S2, S3, S4, S5
8	14-05-2006	5	S1, S2, S3, S4, S5
9	09-07-2006	5	S1, S2, S3, S4, S5
10	12-08-2006	5	S1, S2, S3, S4, S5
11	24-09-2006	5	S1, S2, S3, S4, S5
12	29-10-2006	5	S1, S2, S3, S4, S5
13	19-11-2006	5	S1, S2, S3, S4, S5
14	24-12-2006	5	S1, S2, S3, S4, S5
15	21-01-2007	5	S1, S2, S3, S4, S5
16	25-02-2007	5	S1, S2, S3, S4, S5
17	25-03-2007	5	S1, S2, S3, S4, S5
18	14-04-2007	5	S1, S2, S3, S4, S5
	Total:	**81**	

A short description of the sampler used by Central Water Commission (CWC), Middle Brahmaputra Division, Government of India, Guwahati, Assam

CWC used Punjab Type Silt Sampler to collect suspended sediment samples. It consists of a metallic bottle of one litre capacity, which is held vertically in a metallic frame. The required length of pipe is fitted with the frame to hold the bottle. At the lower end of the pipe a lever is provided to open or close the mouth of the bottle. The lever is operated by a flexible wire passing through the pipe. The system is lowered and when the mouth of the sampling bottle reaches the sampling point, it is opened. It is a very handy sampler with practically zero maintenance. However it suffers from the following drawbacks:

- The direction of intake remains perpendicular to the flow.

i. There is no pressure equalisation system in the sampler due to which there is sudden inrush.

Two photographs of the sampler was taken at the office of Central Water Commission (CWC), Middle Brahmaputra Division, Government of India, Guwahati, Assam, by the researcher, which have been furnished below: