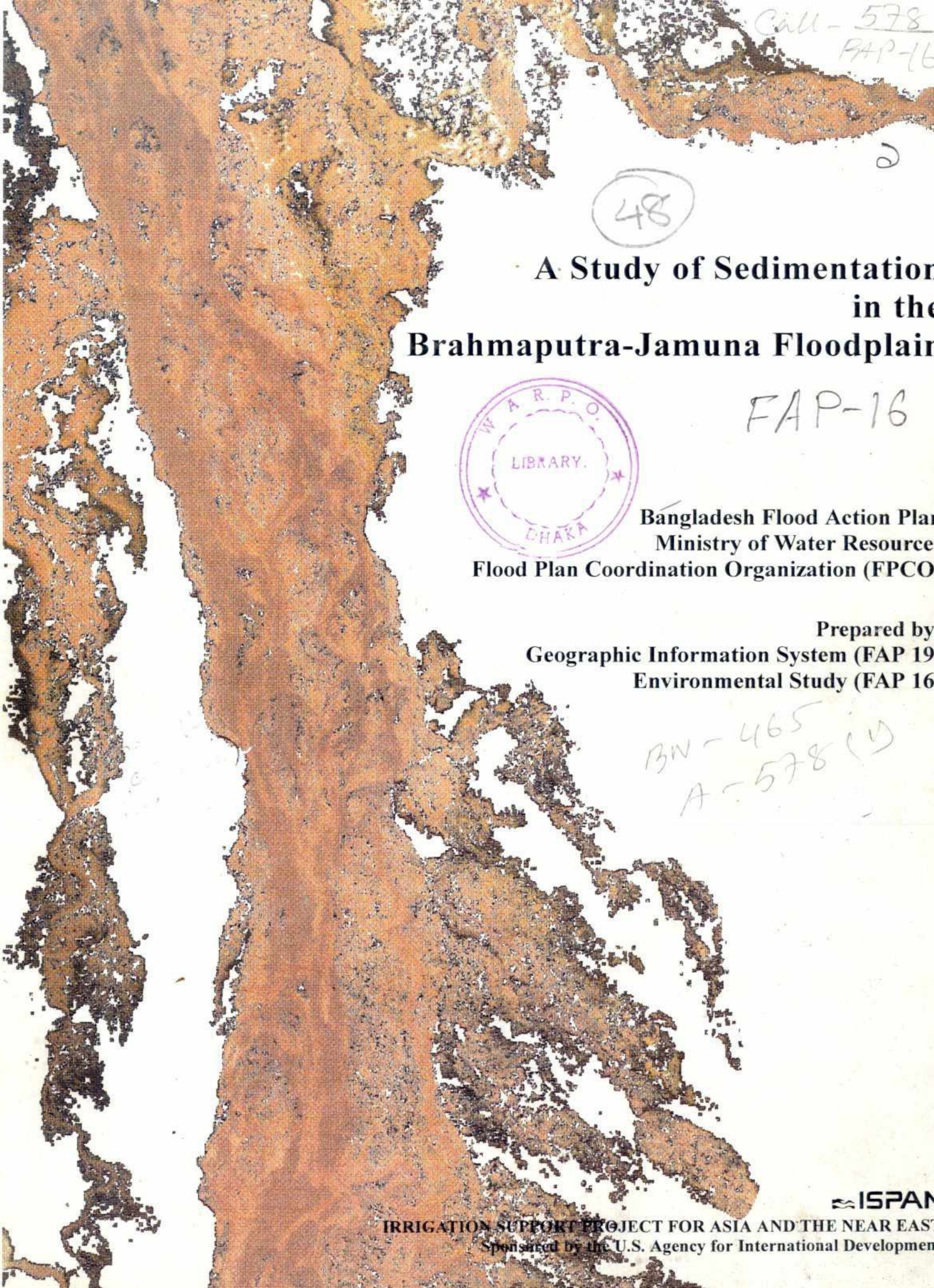

A Study of Sedimentation in the Brahmaputra-Jamuna Floodplain

Bangladesh Flood Action Plan
Ministry of Water Resources
Flood Plan Coordination Organization (FPCO)

Prepared by
Geographic Information System (FAP 19)
Environmental Study (FAP 16)

ISPAN
IRRIGATION SUPPORT PROJECT FOR ASIA AND THE NEAR EAST
Sponsored by the U.S. Agency for International Development

BANGLADESH FLOOD ACTION PLAN

A STUDY OF SEDIMENTATION IN THE BRAHMAPUTRA-JAMUNA FLOODPLAIN

GEOGRAPHIC INFORMATION SYSTEM (FAP 19)

ENVIRONMENTAL STUDY (FAP 16)

Prepared for

The Flood Plan Coordination Organization (FPCO)
of the
Ministry of Water Resources

June 25, 1995

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About the Cover:

The cover shows an enhancement of a Landsat MSS satellite image acquired at the approximate peak of the 1987 flood on August 18th. The image, which was supplied in its original format by the Bangladesh Space and Remote Sensing Organization (SPARRSO), was enhanced by FAP 19 through digital image processing to show relative concentrations of suspended sediment in the flood water. The Jamuna River is shown from the offtake of the Old Brahmaputra River (upper right) and extending south of the Old Dhaleswari River offtake (lower right), a distance of about 100 km.

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ACKNOWLEDGMENTS

This report is the result of a study undertaken during 1993-95 by the Geographic Information System (FAP 19) and the Environmental Study (FAP 16) with the support of the Flood Plan Coordination Organization (FPCO) under the Ministry of Water Resources. The study, conducted under the Bangladesh Flood Action Plan, was funded by the U.S. Agency for International Development (USAID) through the Irrigation Support Project for Asia and the Near East (ISPAN).

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ACRONYMS

AEZ	Agro-ecological zone
ASI	Agro Services International
AST	Agriculture Sector Team
BARC	Bangladesh Agriculture Research Council
BARI	Bangladesh Agriculture Research Institute
BGA	Blue-green algae
BINA	Bangladesh Institute for Nuclear Agriculture
BJRI	Bangladesh Jute Research Institute
BRRI	Bangladesh Rice Research Institute
BTM	Bangladesh Transverse Mercator
BWDB	Bangladesh Water Development Board
CBJET	China-Bangladesh Joint Expert Team
CIDA	Canadian International Development Agency
DEM	Digital elevation model
EDTA	Ethylene di-amine tetra-acetic acid
ERDAS	Earth Resource Data Analysis Systems
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization (United Nations)
FAP	Flood Action Plan
GIS	Geographic Information System
GPS	Global Positioning System
HYV	High-yielding variety
ISPAN	Irrigation Support Project for Asia and the Near East
LEGe	Low-energy intrinsic germanium detector
LGED	Local Government Engineering Department
MIWDFC	Ministry of Irrigation, Water Development, and Flood Control (now Ministry of Water Resources)
MPO	Master Plan Organization
MSS	Multispectral Scanner
PAT	Polygon Attribute Table
RSP	River Survey Project
SOB	Survey of Bangladesh
SRDI	Soil Resources Development Institute
SWMC	Surface Water Modelling Center
TDS	Total dissolved solids
TM	Thematic Mapper
UNDP	United Nation Development Program
WARPO	Water Resources Planning Organization

SUMMARY

1. Objectives

This study aimed to improve basic knowledge about floodplain sedimentation processes in Bangladesh and, to some measure, the contribution that flood-borne sediments make to soil fertility. Hydrologic records were analyzed to estimate the total sediment budget of the Ganges and Brahmaputra rivers. Then, using Geographic Information System (GIS) tools, field teams selected two geographic blocks on the Brahmaputra (Jamuna) floodplain for detailed study of sedimentation and soil fertility during the 1994 monsoon season. Using information derived from the field study and from secondary sources, a GIS model was developed for mapping regional sedimentation regimes.

2. The Study Area

The Brahmaputra River moved into its present Jamuna channel about 200 years ago. The floodplain on its left bank (the Jamuna floodplain) is one of the 23 floodplain physiographic units recognized in Bangladesh. Soil surveys in the 1960s identified Active, Young, and Older Jamuna floodplain subunits and the Old Brahmaputra floodplain. The study area comprised the northern half of the Jamuna floodplain, north of the Dhaleswari River offtake, and an adjoining part of the Old Brahmaputra floodplain.

The Active Jamuna floodplain occupies the braided river channel where constantly shifting secondary and tertiary channels deposit and erode sediments during the annual floods. The relief is rather irregular, and the soils comprise stratified alluvium that is near-neutral in reaction. On the adjoining stable floodplain land there are progressive changes in relief and soils with increasing distance from the main river. An irregular relief of ridges and depressions near the river gives place to a smoother landscape of broad ridges and basins on old floodplain land. In the soils, alluvial stratification is broken up to increasing depths (from 30–50 cm on the Young Jamuna floodplain to 75–100 cm or more on the Old Brahmaputra floodplain); soil properties (subsoil structure, coatings, oxidized mottles) are developed and become more pronounced; topsoils become increasingly acid; the proportion of basin clays increases; and the dominant gray color of Jamuna floodplain soils is replaced by dark gray on the Old Brahmaputra floodplain.

Most floodplain land is seasonally flooded. The highest ridge tops are inundated only intermittently or in years with high river floods. Lower sites are submerged during the monsoon season according to their position in the relief. The proportion of deeply flooded land tends to increase from north to south across the study area. A series of flood embankments built along the Jamuna left bank within the past 25 years appears to have reduced normal flooding depths and the frequency of high floods, but river water still enters the floodplain along distributary channels, through regulators/sluices in embankments, and in years when floods breach embankments.

Farmers grow two or three crops a year over most of the area. Rice is the principal crop; jute, wheat, and other dry-land crops are also grown. Fertilizers are used for all the major crops, and irrigation is widely used in the dry season, except on active floodplain land.

3. Methods

Sediment, soil, and water sampling. Two study blocks measuring 5 km × 2 km were selected for detailed study of sedimentation and soil fertility, one in Sharishabari *thana,* the other in Kalihati and Bhuapur *thanas*. Each block included parts of the Active, Young, and Older Jamuna floodplains. Within each block, 20 sample plots measuring 10 m × 10 m were selected to represent the major flood and sedimentation regimes. At these sites, a marker layer of brick dust, permeable cloths on jute mats, and sediment traps were placed before

the flood season; three replicated subplots were used for each technique. By mid-August 1994, most of these sites had not been inundated, so permeable mats were then placed at an additional six sites on low-lying land near the river.

Because of the very low flood experienced in 1994, many of the selected sites were not inundated. Sediment samples were collected as floodwater receded from six permeable mat sites and five sediment trap sites. None of the sites received enough sediment to make core sampling over the brick-dust layer feasible.

At each sampling site, records were made of the physiographic characteristics, depth and duration of seasonal flooding, farmers' information on the thickness of sediment deposited in average years and in the high 1988 flood, and agronomic practices. Composite topsoil samples were collected from three replicated subplots at each site. Pits were dug so that the profiles of the 12 main soil series occurring in the two blocks could be described, and samples were taken from the main soil horizons. Water samples were collected from rivers and inundated study sites.

Sediment, soil, and water samples were sent to laboratories for determination of particle size, pH, and electrical conductivity, and contents of organic matter, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, zinc, iron, copper, boron, and manganese.

Radiocesium sampling. A total of 41 soil cores were taken in the study blocks, and elsewhere in and around the study area, to collect samples for radiocesium (^{137}Cs), particle size, and bulk density determination. Radiocesium is a fission byproduct of thermonuclear weapons testing in the mid-1950s. Subsequent Cs fallout from the stratosphere onto the land surface provides a means of identifying sediments that have accumulated since the mid-1950s. Two methods were used to assess floodplain sedimentation rates: the maximum depth to which ^{137}Cs was found at individual sites; and a core inventory method seeking to determine the total activity of flood sediments discounting local Cs fallout.

This study used a GIS to map and assess natural resource and infrastructural conditions in the study area. The primary data themes, which represented the agents of the floodplain sedimentation process, were used for baseline mapping, display and analysis of field data, and constructing a GIS model of floodplain sedimentation processes. Interpretation of the primary data yielded other thematic maps for use in the model. In addition, sedimentation rates reported by farmers and rates derived from analysis of soil samples for ^{137}Cs radioisotopes were used. The GIS and Global Positioning System (GPS) receivers were used to map the location of field reconnaissance and sediment sampling sites.

4. Findings

Sediment and Soils. Because of the very low flood experienced in 1994, few of the sampling sites received any sediment deposit. Only two traps received significant amounts, at rates of 7.67 and 35.67 tons/ha. At the six supplementary sites, where permeable mats were located in August, five sites received 2–6 mm of sediment; the other, adjacent to an active river channel, received 300 mm of coarse sediment. Contents of all nutrients were high or moderate in both trap and mat samples, except for zinc in mat samples and for most nutrients in the thick sandy deposit.

Organic matter contents of topsoils tended to increase with floodplain age (from 0.3–1.1 percent on the active floodplain to 1.0–2.5 percent on the older floodplain) and topsoils tended to become more acid (from pH 6.5–7.7 on the active floodplain to 6.3–6.8 on the older floodplain).

Topsoils on the active and young floodplains were mainly neutral to mildly alkaline; those on the older floodplain were moderately acid. Subsurface layers were mainly neutral to mildly alkaline.

Radiocesium analyses. Radiocesium analyses showed that the depth of human-induced mixing (plowing) of the floodplain sediment surface was confined to the upper 10 cm. This validates the usefulness of the excess depth of penetration technique as an accurate and simple means of determining total sedimentation at sites since the introduction of radiocesium in 1956. The data also exhibited a strong correlation of the ^{137}Cs activity with fine-grained particles. After correction for the grain size, bulk density of samples, and atmospheric versus river input, the inventory approach yielded accumulation rates that agreed well with the simpler technique based on depth of penetration. The resulting ~40 year average sedimentation rates from the 41 core sites were used to provide quantitative point data for floodplain physiographic zonations in the GIS regional model.

Annual sedimentation rates generated by the GIS model for the study area ranged from 0 to 74 mm/yr with an average rate of 7.6 mm/yr. The total estimated annual sediment for the study area was some 29 million metric tons. Areas annually receiving 10 mm or less of sediment account for only 25 percent of the total sediments but covered 75 percent of the study area. According to the model, approximately 84 percent of the sediment deposited annually is within 0.5 km of a sediment source, but only 27 percent of the study area is within this distance. A map of cumulative sediment deposition over the 1954-1994 period, which corresponds with that of the ^{137}Cs analysis of soil samples, was also generated by the GIS model.

As would be expected by their definitions, the Active and Young Jamuna floodplains had higher average annual sedimentation rates than the less active Older Jamuna and Old Brahmaputra floodplains.

5. Assessment

Sedimentation zones. Sediment rates determined by ^{137}Cs analysis demonstrate that sedimentation is a function of distance from a river source, including distributaries and *khals*. The rates correlate closely with floodplain age, averaging >1.3 cm/yr on the Active Jamuna floodplain, 1.24 cm/yr on the Young Jamuna floodplain, 0.29 cm/yr on the Older Jamuna, and 0.15 cm/yr on the Old Brahmaputra floodplain. The rates obtained by ^{137}Cs analysis corresponded somewhat with figures obtained from farmer interviews.

Topographic controls. Rapid sedimentation rates on land alongside river channels creates elevated natural levees, crevasse splays, and point bars that can form a barrier to sedimentation across flood-plains. Among other things, this may form basins between levees along main, secondary, and tertiary river channels. Such low-lying land may be flooded by rainwater and a raised groundwater table rather than by sediment-laden river water. Wash of sediment from high areas to depressions during rainfall gradually reduces relief on older floodplain areas. The latter phenomenon has implications for interpreting sedimentation rates from Cs data because Cs analysis is unable to differentiate between new sediment input and locally reworked sediment.

Infrastructure. The construction of flood embankments along the Jamuna since the late 1960s makes it difficult to assess natural sedimentation rates on the floodplain. However, even in protected areas, river water can still flood the land through distributary rivers and *khals,* when regulators and sluices in the embankments are opened, and in exceptionally high flood years (such as 1988) when embankments are breached. Since farmers uniformly mentioned a decrease in flood depth in their fields following embankment construction, it is assumed that sedimentation rates have also decreased.

Large floods. The Cs data provided a sedimentation rate averaged over about 40 years. Farmer interviews indicated that greater amounts of sediment were deposited in high flood years. This input from large floods is particularly significant on older floodplain land where sedimentation rates in normal years are negligible. Analysis of a satellite image taken during the high

1987 flood also shows that the flow of turbid water alongside the floodplain becomes an important means of sediment delivery to older floodplain areas in large floods.

5.1 Sedimentation and Soil Development

The soil profile descriptions and laboratory data presented show the rapidity with which raw alluvium changes into soil with pronounced profile characteristics. They also show that the upper soil layers and depression sites have finer materials than occur in the substratum and on ridge sites respectively. However, on the Older Jamuna and Old Brahmaputra floodplains the vertical and lateral fining processes are reversed in the topsoil, which has less clay than the underlying subsoil. This loss of clay from the topsoil is attributed to a process of acidification and clay destruction found in seasonally flooded soils.

Recent alluvium has stratified layers immediately below the plowed layer. In developed soils, stratification has been broken up by biological mixing, and a B horizon has formed. This horizon is characterized by soil structure, oxidation mottles, and sometimes coatings along cracks and voids. The thickness of the B horizon tends to increase with distance from the active floodplain towards the Old Brahmaputra floodplain. Soils on the Active and Young Jamuna floodplains are near-neutral in reaction in all layers and generally have low organic matter contents. Soils on the Older Jamuna and Old Brahmaputra floodplains have moderately to strongly acid topsoils, and have more organic matter than the younger soils, especially in basin sites. These soil characteristics indicate that flood-borne sedimentation rates must be minimal for older floodplain land.

The findings suggest that the most consistent parameter that could be used to indicate whether or not soils are receiving significant amounts of new river alluvium is the occurrence of a lower pH value in the topsoil than in the subsoil. Soil color is not a wholly reliable indicator of soil age, although young soils generally have paler gray topsoils and lower organic matter contents than old soils, and many old floodplain soils have a more strongly oxidized subsoil than occurs in young soils.

5.2 Soil Fertility

Nutrition in sediments. At the sites that received sediments, the laboratory data indicate considerably higher levels of nitrogen, phosphorus, and sulphur than the assumed crop requirements, but levels of potassium are considerably below requirements. However, for various reasons, these results should be treated with caution, not least because they do not correspond to farmers' fertilizer practices in the area. It is possible that the higher levels of organic matter and major plant nutrients present in sediment samples than were found in adjoining topsoil samples reflect the fact that the algal residues on the surface formed a much higher proportion of the total sample in the thin sediment deposits than in 10 cm-thick topsoil samples.

Soil nutrient status. Comparison of the laboratory data for soil profiles from different physiographic units shows that soil nutrient status is not directly linked with sedimentation. Soils on the Active and Young Jamuna floodplains, which receive the most new sediment, do not have higher nutrient contents than soils on older floodplains, which receive negligible amounts of sediments. Also, young, unleached soils do not necessarily have higher nutrient contents than older soils with acid topsoils. The higher nutrient contents of soils on the older floodplain probably is linked to their higher contents of clay and organic matter. This study did not measure the contributions of blue-green algae and other biological agents to soil fertility.

Vertical accretion of sediments from overbank flooding were represented in the GIS model using a distance function for the natural levees and physiography-based minimum annual deposition rates for floodplain/backswamp areas. The deposition rates predicted by the model are relatively high immediately adjacent to the source of sediment and then drop off rapidly to minimum thresholds according to physiographic regions.

The GIS model estimate of average annual sedimentation depth, 7.6 mm/yr, compares favorably with the rates of 7.5 mm/yr and 11.5 mm/yr from a sediment budget for the Jamuna, Ganges, and Padma river system. Farmer reports of relative sediment depths were similar to GIS model results. However, averages of mean sedimentation rates reported by farmers disagreed with the GIS model results for the various physiographic units.

6. Conclusions and Recommendations

The findings of this study provided important new information on the rates and location of sedimentation on the Jamuna floodplain, on soil fertility, and on techniques of sediment sampling. Important lessons were learned that can guide future studies.

Sedimentation. It is possible that sedimentation rates were underestimated on the active floodplain because 1994 was a low flood year and because it was impossible to obtain deep cores for Cs analysis. The Cs sampling technique also did not allow a distinction to be made between sediment derived from river floods and sediment washed into depressions by local runoff.

It is difficult to extrapolate the study findings to other floodplain areas in other than a general sense. That is because of differences in flooding characteristics between the study area and the southern part of the Jamuna floodplain, and because each floodplain region in Bangladesh has unique physical and hydrological characteristics.

Soil fertility. Important findings were that: the small amounts of sediment deposited on sampling sites in 1994 may have yielded unrepresentative levels of organic matter and plant nutrients; little relationship apparently exists between laboratory data and soil fertility status; and soil nutrient levels determined by laboratory analysis generally are lower in soils that receive sediment increments than in those that do not. It would be unsafe to extrapolate the study's findings to other floodplain areas because of differences in physiography, hydrology, and mineralogy between floodplain regions.

Techniques. Important lessons learned from this study about techniques were that: GIS mapping and analysis is very useful for designing a sedimentation study and presenting results, soil survey reports provide a useful guide to the selection of geomorphic units, but may need updating where subsequent changes have occurred in river channels or infrastructure; farmer interviews are a valuable means of obtaining information about flooding and sedimentation when averaged for physiographic regions; permeable mats and traps proved to be satisfactory methods for sediment collection, but the use of a marker layer of brick dust was unsatisfactory where sedimentation was slight; the ^{137}Cs technique for measuring sediment accumulation rates proved valuable; and laboratory analysis of sediment, soil, and water samples is not a reliable means to determine their nutrient values.

Comparisons with other major rivers. The development and evolution of Bangladesh's floodplains have similarities to and differences from other major river floodplains. As in the floodplains of other major rivers rising in high mountain regions, the enormous size of the Ganges-Brahmaputra catchment tends to produce floods in a particular season, the maximum sediment discharge precedes the maximum water discharge, and the sediments carried to the floodplain are little weathered and of high potential fertility. Sedimentation rates and overbank processes are similar to those observed in other major river systems, except that channel migration rates in the Jamuna River are exceptionally high, distributary channels play a more significant role in delivering sediment onto floodplains, and tectonic activity may play a larger role in channel avulsions and migrations, and in offsetting the elevation of floodplain land by sediment deposition. River control works along Bangladesh's rivers are more recent and less complete than along such major rivers as the Mississippi, Nile, and Rhine, and the environmental impacts to date have been correspondingly less.

Arising from these international comparisons, a number of universal scientific problems that are relevant to Bangladesh's situation need to be addressed. They include: river sediment budgets; the effects of large floods, down-gradient flood flow, and floodplain vegetation on sedimentation; the effect of a rising sea level; tectonic and compaction-induced subsidence; and how changes in river morphology affect overbank flow.

River control and sedimentation. Two of the study's findings have important implications for the planning and operation of flood protection works. One is that the bulk of river sediments are deposited on narrow strips along active river channels with substantially lesser amounts being deposited in young floodplains; most older floodplain land receive little or no new sediments. The other is that the soils receiving significant amounts of new sediment do not have higher nutrient contents than soils that do not receive new sediment. It appears that reduction in sediments on the floodplain due to construction of embankments would, therefore, have a negligible direct effect on the nutrient status of most floodplain soils. However, protection works that reduced the depth and duration of seasonal flooding could reduce fertility benefits derived from biological sources, which may be significant but were not measured by this study.

GIS modelling. Results of the GIS model appear plausible with respect to rates derived from sediment balance data and relative to most of the field data. The average depths reported by farmers indicates that the GIS model may be substantially underestimating rates in the Active and Young Jamuna floodplains and overestimating in the Older Jamuna and Old Brahmaputra floodplains. The basic concept and fundamentals of the GIS model appear sound, however, and an improved field sampling strategy and statistical analysis based on floodplain geomorphology and physiography could improve it considerably.

Future studies. The following studies are recommended to confirm, supplement, and extend the 1994 study's findings.

1. Sedimentation studies should be continued on the Jamuna floodplain in 1995. The study block in Sharishabari *thana* should be retained, but it should be extended onto more active floodplain land and onto the Old Brahmaputra floodplain. A new block should be selected in Daulatpur *thana* to study conditions in the southern part of the Jamuna floodplain, and observations should be made at intervals alongside the Dhaka-Aricha road crossing this part of the floodplain.

2. Sampling points in study blocks should be on a grid pattern to facilitate statistical analysis of results. The sampling methods used in 1994, including farmer interviews and cesium analyses, should be retained. Additional observations should be made in cropped fields adjoining sample sites to ascertain whether vegetation influences the amount of sediment deposited.

3. Sediment and topsoil samples should be analyzed to determine particle size, reaction (pH), and organic matter contents. In view of the poor correlation this study found between laboratory results and apparent crop nutrient requirements, it is not considered necessary to determine other nutrient contents.

4. Results of agricultural research trials and fertilizer demonstrations in the study area should be reviewed and analyzed to obtain direct evidence of the impact of sedimentation on soil fertility and crop

performance. To the extent possible, sites used during the past five years should be identified and their physiography and soils classified.

5. Future soil fertility studies should assess the contributions of blue-green algae and other biological agents of flooded environments to soil fertility.

6. As soon as possible, sedimentation studies should be extended to other floodplain regions to augment the information gained on the Jamuna floodplain and to refine the GIS sedimentation model.

7. The government (with international assistance as necessary) should undertake a program of basic research studies to determine appropriate methods of soil nutrient analysis for seasonally flooded soils, to assess the contributions of biological agents to soil fertility in different floodplain environments, and to identify the processes of clay and organic matter accumulation found in old floodplain basin soils.

Chapter 1

INTRODUCTION

1.1 Introduction

Most of Bangladesh is on the delta formed by three of the world's major rivers, the Ganges, Brahmaputra, and Meghna. These rivers, and many of the country's minor rivers, rise outside the national boundaries of Bangladesh and make up the Ganges-Brahmaputra-Meghna system (Figure 1.1). This system, draining a basin of some 1.76 million square kilometers, carries not only snowmelt from the Himalayas but also runoff from some of the highest rainfall areas of the world. Over millennia, the sediments carried by the huge discharges of these rivers have built a broad delta, forming most of the land area of Bangladesh and the submerged delta plain in the Bay of Bengal.

Two distinct sedimentation processes contribute to this delta's formation. The most obvious occurs when shifting river channels deposit volumes of river-borne sediments in a single monsoon season (lateral accretion). Another process occurs when

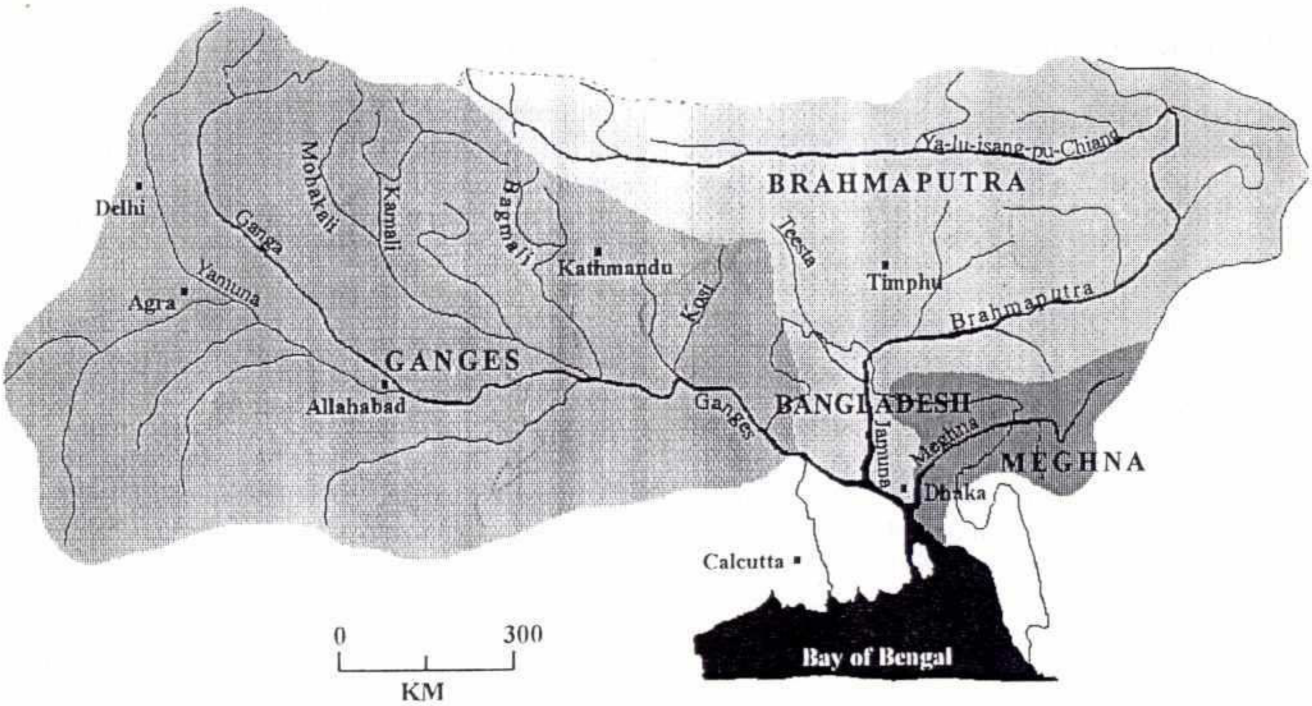

Figure 1.1 The Ganges, Brahmaputra, and Meghna River Catchment Areas

sediment-laden waters spill onto the floodplains, and finer suspended sediment particles settle as the floodwater recedes (vertical accretion). These natural sedimentation processes have been and continue to be disrupted by the construction of roads, bridges and culverts, embankments, and flood control or water management structures. The effects these interventions have on the complex hydrology and environment of Bangladesh are of growing interest to planners and resource managers.

While existing literature contains considerable information on deltas and their formation, hard data on floodplain sedimentation are scarce, and the subject is not well understood. Reliable data and knowledge about the complex sedimentation processes of Bangladesh's floodplains are particularly rare. Studies that have attempted to measure floodplain sedimentation rates in the country are few and have yielded little quantitative information. Also poorly understood, although long debated, is the role deposited sediments play in soil fertility and agricultural production in Bangladesh. Recently accelerated floodplain development and the possibility that the Flood Action Plan (FAP) and other programs will undertake further water resources interventions have created an urgent need to improve the state of knowledge about floodplain sedimentation.

1.2 Study Objectives and Approach

The overall objectives of this study were to improve basic knowledge about floodplain sedimentation processes in Bangladesh and to enhance understanding of the contribution made by flood-borne sediments to the formation of soils and their fertility. The study sought to achieve these broad objectives by performing the following tasks:

1. Assimilate relevant data and literature from local, regional, and international sources.
2. Characterize a floodplain study area as to its hydrology, geomorphology, soil properties, infrastructure, and other properties that are defined by, or are controlling factors of, sedimentation processes.
3. Monitor sedimentation processes for a single monsoon flood season; collect deposited sediments, quantify their deposition rate and characterize their physical and chemical characteristics.
4. Test various techniques for sampling sediments deposited on the floodplain.
5. Develop techniques for mapping and modelling the rate and distribution of sediments over larger floodplain areas.

The study delivers three increasingly detailed levels of knowledge about floodplain sedimentation. At its broadest level, the study developed first-order estimates of the total sediment budget of the Ganges and Brahmaputra rivers based on analysis of existing hydrological records. The intermediate level of investigation studied a large area encompassing part of the east-bank floodplain of the Brahmaputra (Jamuna) River. FAP 19 (Geographical Information System) compiled information for this study area using satellite imagery, digital mapping tools, and a Geographic Information System (GIS). A field team then used the maps as aids in studying floodplain sedimentation and in selecting sites for soil-core sampling. Laboratory testing of the core samples for an artificial radionuclide (^{137}Cs) yielded data on the integrated amount of sedimentation that has occurred over the past 40 years.

At its most detailed level, the study surveyed and sampled two representative blocks in the study area. Field surveys, assisted by recent aerial photography and the Global Positioning System (GPS), generated detailed maps of each block. Field personnel also tested several methods for direct sampling of sediments deposited during the 1994 monsoon season. Sediment and soil samples were collected and their physical and chemical properties were analyzed. The results of these tests, combined with the field study, facilitated understanding of local sedimentation processes. It also allowed the study to estimate flood-borne sediment deposition rates and assess the contribution sediments made to agricultural soil resources and their fertility.

1.3 Background

1.3.1 Floodplain Sedimentation: The State of Knowledge

Sedimentary strata deposited by rivers are broadly divisible into lateral and overbank deposits. Lateral deposits are formed by channel migration, and overbank deposits are formed by vertical accretion during floods. Together these mechanisms generate a floodplain. Geomorphologists define a floodplain as "the largely horizontally bedded alluvial landform adjacent to a river channel, separated from the channel by natural levees, and built of sediment transported by the present flow-regime" (Nanson and Croke 1992). The earliest detailed studies (Wolman and Leopold 1957) concluded that lateral processes (e.g., point-bar accretion, braid channel evolution) predominantly controlled the formation and evolution of the floodplain. This belief, widely held in the 1960s and 1970s, helped focus research efforts by geomorphologists, hydraulic engineers, and sedimentologists. Today, as a result, advanced models exist for quantifying lateral processes of channel development and evolution. More recently, however, Nanson (1986) recognized that "rather than a single model of floodplain formation, there is an array of processes leading to different floodplain types in different environments," including some dominated by vertical accretion. Theoretical models predict that, through avulsion, the channel belt eventually will return to a given location, but at a different elevation, thereby preserving and incorporating finer-grained overbank deposits in the alluvial stratigraphy (Bridge 1984). Further evidence of the importance of vertical accretion in floodplains can be found in the geologic record, where many preserved deposits have a ratio of floodplain to channel deposits >1 (Wright and Marriott 1993).

Despite general consensus today that overbank deposition plays an important role in total river sediment budget and floodplain architecture, comprehensive quantitative models of overbank deposition are not yet available. This is primarily due to (1) the limited number of 'ground-truthing' studies to date that have made direct measurements of sedimentation rates in floodplains and (2) the complexity of overbank sediment transport. The following sections summarize the current state of knowledge about these two factors.

1.3.2 Measuring Sediment Deposition in Floodplains

Table 1.1 summarizes the methods various investigators have used to measure floodplain sedimentation. These techniques are divisible into (1) direct measurements of layer thickness using mats, traps, and introduced or *in situ* horizons and (2) indirect measurements using particle-associated tracers (Cs, trace metals) or measurements of water and sediment fluxes. The methodology of an individual technique, and/or the period over which it integrates sedimentation, limit its applicability. For example, ^{137}Cs inventories integrate sediment deposition since 1956 (soon after the onset of H-bomb testing). This limits their usefulness as a tool for examining individual floods. The present study employed several methods suited to Bangladesh's floodplains (mats, marker beds, traps, ^{137}Cs, and water/sediment discharge) to assess their applicability and cover a range of time scales.

Although measurements of floodplain sedimentation have been made on only a few of the world's river systems (Table 1.2), the body of data is sufficient to identify several major controls on sediment delivery via overbank flow. First, there is no direct correlation between river size (water/sediment discharge) and the percentage of sediment stored on the floodplain and, therefore, on sedimentation rates. The unique characteristics of each river system (e.g., climate, catchment elevation, stream gradient, local geology, etc.) determine the sediment concentration in river water and the nature of the 'flood pulse' that results in sedimentation. Second, overbank flow is highly variable between river systems and temporally variable within individual systems, subject to the frequency, regularity, duration, rate of rise and fall, and amplitude of floods (Junk et al. 1989). In some rivers, for example, large floods may contribute

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Table 1.1 Techniques for Measuring Overbank Sedimentation Rates in River Floodplains

Technique	Description	Major Limitations
Marker Beds	Distribute datum layer of distinct material (brick dust, fluorescent-dyed sediment, etc.) on the sediment surface prior to deposition.	• large errors for deposition of <1 cm • removal and diffusive mixing of marker bed
Flood Layers	Direct measurement of thickness of sediment layer deposited in a single flood.	• large errors for deposition of <1 cm • infrequent events • not representative of mean input onto floodplain
Buried Horizons	Integrated deposition over *in situ* datum surfaces (soils, peat layers, etc.) of known age (dated by radiocarbon analysis).	• errors in age date of surface • horizon not laterally isochronous • single, integrated deposition rate
Mats	Attach a mat (wood, carpet, jute, etc.) to the sediment surface prior to deposition.	• large errors for deposition of <1 cm • deposition may not reflect rates on surrounding sediment surface because of different permeability, response to bed stress, etc.
Sediment Traps	Deploy funnel-shaped collectors at the sediment surface attached to traps filled with preservative (e.g., formalin, etc.) to examine chemistry of input material.	• expensive and easily disturbed • must be redeployed following each measurement • deposition may not reflect rates on surrounding sediment surface
Dendro-geomorphology	Tree-ring dating of vegetation that has colonized floodplain surfaces (see Hupp and Morris 1990).	• difficulty interpreting geomorphological relationships • temporal spread of individual colonization • single, integrated deposition rate
Trace Metals	Depth of occurrence of high-levels of trace metals (As, Cu, etc.) introduced into rivers by mining in the drainage basin at a known time (see Marron 1992).	• not present in all river systems • single, integrated deposition rate
^{137}Cs inventory	Particle-reactive tracer introduced into atmosphere by H-bomb testing beginning in 1954–55 (see Walling and Qingping 1992).	• two sources (river sediment, direct atmospheric flux) • expensive • single, integrated deposition rate
Water sampling/ Current meters	Direct measurement of suspended sediment concentration and water vectors on the floodplain during overbank flow (see Mertes 1994).	• logistically difficult • spatial and temporal heterogeneity of suspended sediment flux • bedload transport into floodplain • two mechanisms of suspended-sediment flux (diffusion, advective transport)
Water/Sediment discharge	Monitoring sediment discharge in river above and below floodplain reach to obtain net loss to overbank sedimentation.	• large measurement errors • no information yielded on spatial variability • difficult to measure at peak flood

Table 1.2 Summary of River Studies That Quantify Floodplain Sedimentation Rates on Time Scales of 10–10,000 Years

River	Average Water Discharge (m^3/sec)	Measurement Technique	Sediment Accumulation Rate (cm/yr)	Time Period (years)	Reference
Culm (UK)	~5	Cs inventories	0–0.7	1954–1987	Walling and Bradley (1989)
Ilme (Germany)	~6	Radiocarbon dating	0.03	1400–present	Hagedorn and Rother (1992)
Fyrisan (Sweden)	7.0	50×50 cm mats	0.0005–0.015	1986	Gretener and Stromquist (1987)
Coon Creek (USA)	~8	Soil layers	1.5 (6–15)*	1853–1975	Trimble (1983)
Belle Fourche (USA)	10.2	Trace metal (As) contamination	0.9–1.5	1876–1978	Marron (1992)
Maluna Creek (Aust)	~40	Cs inventories	0.3	1954–1986	Nanson et al. (1992)
Missouri (USA)	3,000	Flood layers	50–200	1982	Ritter (1988)
Fly (New Guinea)	6,000	Trace metal (Cu) contamination	0–0.2	1981–1990	Higgins (1990), Day et al. (1992)
Jamuna (Bangladesh)	19,600	Cs inventories/excess penetration	0–4	1954–1994	This study
Mississippi (USA)	20,000	Flood layer	10–84†	1973 flood	Kesel et al. (1974)
Amazon (Brazil)	100,000	Water sampling/current meters	290–580‡	1987 flood	Mertes (1994)

* Pre-settlement (following anthropogenic denudation of forest cover in drainage basin)
† Natural levee
‡ Maximum rates observed on the natural levee at peak flood

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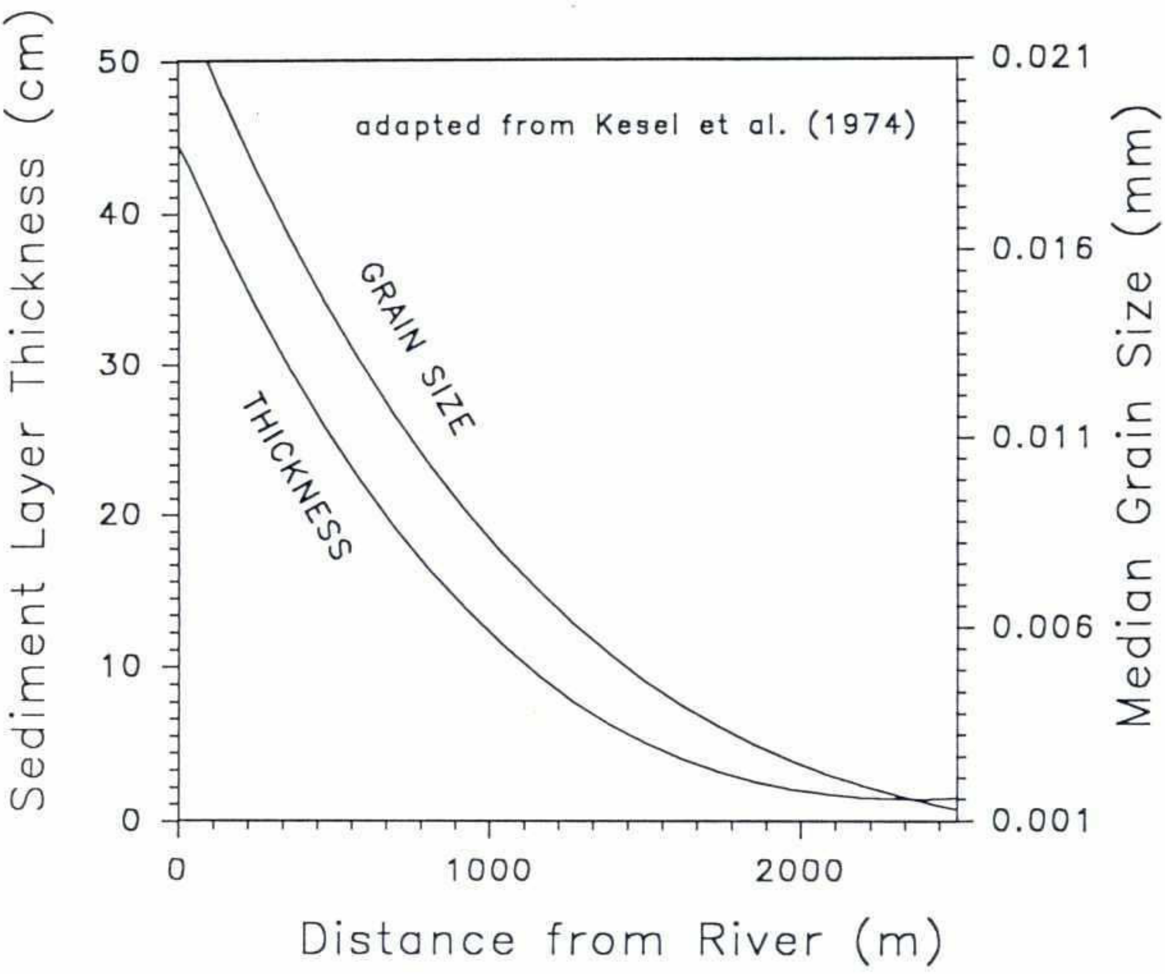

Figure 1.2 **Flood Layer Thickness, 1973 Mississippi River Flood**

more sediment to the floodplain than all "normal" floods combined (Kesel et al. 1974, Gupta 1988, Ritter 1988). In other instances, such floods can partially denude the floodplain surface (Nanson 1986). This suggests that caution should be exercised when comparing sedimentation rates either between rivers or integrated over different time scales.

Previous studies also reveal that sedimentation rates on the floodplain surface have complex spatial variability. As a rule, sediment deposition decreases exponentially with distance from the river source. This is evident in the flood layer thickness of the 1973 Mississippi River flood (Figure 1.2). As the flood spreads out onto the floodplain, decreasing overbank flow velocity reduces its sediment transport competence. Working in combination with diffusion processes, this causes an exponential decrease in the size of the particles deposited farther from the channel. This process forms a coarser-grained natural levee near the channel, grading with distance into a finer-grained, lower-elevation (because of slower sedimentation) floodplain.

This simple sedimentation pattern is complicated, however, by along-stream variation in overbank flow rates and concentrations. The former can result in point-source introductions onto the floodplain that generate crevasse splay deposits and an irregular levee elevation, which may change the path that future overbank flows take. Walling et al. (1992) has also traced spatial variability to local floodplain relief features (levees, channels, point bars, etc.) left behind by migration of the main and distributary channels and by human alterations.

1.3.3 Floodplain Sedimentation Models

The input-output relationship of turbid water flux to a floodplain has been summarized by Hughes (1980) and Lewin and Hughes (1980) as the net volume increase with time (dV/dt):

$$\frac{dV}{dt} = Q_{br} + Q_{over} + Q_{off} + Q_{uf} - Q_{ebb} - Q_{df}$$

Water enters as: (1) breach flow through the natural levee (Q_{br}), forming crevasse splay deposits; (2) overbank flow (Q_{over}), raising the natural levee elevation; (3) flooding of river offtakes (Q_{off}); and (4) down-gradient flow from upstream floodplain reaches (Q_{uf}). Turbid water is lost through ebb flow (Q_{ebb}) of water returning overbank via levee breaches or offtakes and by output to downstream floodplain reaches (Q_{df}). Turbid water flow on the floodplain surface is affected by non-turbid standing water from precipitation and flood-induced rise of the water table. Hughes (1980) has shown that the processes of inundation and recession for any river floodplain depend upon the shape of the flood hydrograph and the floodplain planform. Further, because each flood has a unique hydrograph, no clear-cut relationship exists between total influx from the channel (Q_{in}) and the volume of turbid water stored on any floodplain reach. In reality, water volumes on the floodplain at a certain inundation level may differ from those at the same stage during recession.

The inundation process is so complex that only a few simple depositional models have been developed for predicting sediment delivery to the floodplain. Pizzuto (1987), for example, describes the diffusion of a vertically integrated sediment concentration across the floodplain during a steady overbank flow. The steady-state solution predicts the thickness of sediment deposited with distance from the channel using particle settling velocities, vertically integrated sediment concentration of the overbank flow, and laboratory-derived diffusivity values. The resulting model data are fitted with observed rates on a small river in Pennsylvania (USA) with an average error of ± 7 percent. Unique solutions are possible for a variety of particle-size classes. This approach, however, does not consider other modes of overbank sediment transport (e.g., bedload transport, advective transport), nor does it consider how overbank flow interacts with the other factors mentioned in the equation above.

Several studies have shown that aggradation of the floodplain surface decreases with time and elevation, i.e., asymptotically (see Wright and Marriott 1993). Continued sedimentation-induced raising of the floodplain surface over time places it above the reach of all but the highest floods. This process is magnified by natural levee formation and diminished with increasing subsidence rates on the floodplain. Howard (1992) models deposition rate on the floodplain as a function of floodplain height (maximum floodplain height [E_{max}] relative to local floodplain height [E_{act}]). Diffusion length scale (λ) is used to predict exponential decrease in the coarse suspended load deposition rate (μ) with distance from the channel (as in the Pizzuto model), while the fine-grained fraction deposition rate (ν) is modelled as distance-independent (e.g., one rate over the entire flooded area). The resulting model

$$\text{Depostion rate } (\phi) = (E_{max} - E_{act})\,[\nu + \mu \exp(-D/\lambda)]$$

in which D = distance to the nearest channel, is a basic representation of the rapid deposition on the levee as well as more distant overbank sedimentation. This model was the starting point for the floodplain sedimentation model developed in the present study.

1.3.4 Floodplain Sedimentation in Bangladesh

As previously noted, most of Bangladesh lies within the deltaic plain of the Ganges-Brahmaputra-

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Table 1.3 **Estimates of Total Annual Water and Sediment Discharge for the Major Rivers of Bangladesh**

River	Average Annual Water Discharge (m^3/s)	Estimates of Average Annual Sediment Discharge (10^6 ton/yr)			
		Coleman (1969)	MPO (1987)	CBJET (1991)	RSP (1994)
Brahmaputra	19,600	608	387	499	586
Ganges	11,000	479	212	196	549
Meghna	4,800	13	-	-	-

Meghna fluvial system. These three rivers, along with approximately 230 tributaries and distributaries, crisscross the predominantly low-gradient and low-elevation plain and debouch into the Bay of Bengal. Table 1.3 summarizes the water and sediment discharges of the three rivers.

Of these major rivers, the Brahmaputra-Jamuna has the highest downstream gradient and is therefore highly charged with sediment (Barua 1994). The 240-km reach in Bangladesh has two major tributaries, the Teesta and Atrai rivers, and several distributaries (Old Brahmaputra, Dhaleswari, etc.). The major floodplains of the Brahmaputra-Jamuna system are the Teesta; Karatoya-Bangali; Lower Atrai; Old Brahmaputra; and the active, young, and old Jamuna (FAO 1988).

In Bangladesh, the Ganges receives water from one tributary, the Mahananda, and has only one major distributary, the Gorai. Floodplain areas include the active Ganges, and high and low Ganges (FAO 1988).

The Meghna, the smallest of the three major systems, has the highest water yield per unit area of catchment (Barua 1994). The Meghna's major tributaries are the Surma and Kushiyara, and its floodplains include the Meghna, Surma-Kushiyara, and the Sylhet Basin (FAO 1988).

Annual monsoon-season flooding of these three river systems inundates, on average, about 18 percent of Bangladesh (MPO 1987). However, unusually large floods, like the flood of 1988, can inundate as much as 54 percent of the country. Rising river levels in the wet season (June September) result in overbank and offtake flow, particularly in high-flood years, that supply sediment-laden water to the physiographic units of the floodplain (e.g., active floodplain, natural levee, and flood basin). It is clear from existing research that Bangladesh floodplains vary considerably in the quantity and character of sediment they receive from rivers (Alam et al. 1990). Among the factors involved are the flooding characteristics of the individual rivers, floodplain elevation relative to the river, the presence of offtakes, and increasingly, the presence of embankments.

Considerable sedimentological and chemical information on the nature of sediments and soils in individual Bangladesh floodplains is available from the shallow tubewell and deep-well drilling program of the BWDB, and from the regional studies of the Soil Survey (see Section 1.4.1) and Bangladesh Geological Survey. However, virtually no quantitative information is available about vertical accretion rates or total sediment fluxes onto the floodplains. First-order estimates suggest that a significant portion of the total sediment load of the rivers is stored in the floodplains, as much as 40–80 percent according to Milliman and Syvitski (1992). In other words, as little as 20–40 percent of the sediment carried by the rivers of Bangladesh may be discharged into the Bay of Bengal. Of course, much of the sediment is only "stored" on the floodplain until it re-enters the channel via lateral bank erosion. The average storage time is an important determinant of soil development.

Whitton et al. (1988) recorded sediment deposition on deep-water paddy land on the Jamuna floodplain near Manikganj between July and November. Sediment deposition was highest in July, when it was 215 g/m^2/week (0.016 cm depth, using a bulk density of 1.35 g/cm^3), and lowest in the first week of November, when it was 35 g/m^2/week (0.003 cm). Elsewhere, they found that the annual deposition ranged from a low of 36 g/m^2 (0.003 cm) at Daudkandi on the Meghna to 5,353 g/m^2 (0.40 cm) at Mohadevpur near the Jamuna-Ganges confluence. The median annual deposition for all sites was 408 g/m^2 (0.03 cm). Sites near the river Meghna had the lowest deposition rates, which ranged from 36 to 187 g/m^2 (0.003 to 0.014 cm), while sites near the Jamuna had the highest.

1.4 Soils and Soil Fertility

This section provides a brief introduction to information available to this study on Bangladesh's floodplain soils and their fertility. It provides a basis for understanding and interpreting the study findings regarding the role of sedimentation in maintaining soil fertility on Bangladesh's floodplains. More detailed information on the soils of the study area is given in Chapter 2.

1.4.1 Soil Development

Virtually the whole of Bangladesh was covered by reconnaissance soil surveys in the 1960s and 1970s, and comprehensive reports were published for administrative districts and subdivisions (e.g., SRDI 1967a, b). The information collected on these surveys is summarized in FAO (1971), FAO (1988), and Brammer (1995a).

The floodplains that occupy about 80 percent of the country have been formed by the country's main rivers: the Brahmaputra-Jamuna, Teesta, and Ganges, which bring sediments rich in weatherable minerals from crystalline rocks in the Himalayas; and smaller rivers in the north and east, which bring in coarser sediments derived from sedimentary rocks in adjoining hill areas of Bangladesh, Assam, and Tripura (Huizing 1971). Active, meander, piedmont, estuarine, and tidal floodplains are differentiated. A great diversity of soils has developed on these different landscapes, and soil patterns often are complex.

In many areas, the soil surveys recognized active, young, and old floodplain landscapes. Active floodplains occupy land within and adjacent to the main rivers where shifting channels deposit and erode new sediments during the annual floods. New alluvium is stratified (in layers). On most floodplains, this alluvium is neutral or slightly alkaline in reaction, but new Ganges and Lower Meghna alluvium is moderately alkaline and calcareous.

The soils survey describes young and old floodplains as virtually stable land that the main river channel has moved away from, but they are crossed by tributary or distributary channels that vary from active to moribund (silted up). On these floodplains, the processes of soil formation dominate over sediment deposition, as evidenced by soil characteristics: i.e., the original alluvial stratification has been broken up by biological mixing; the subsoil has developed structure and oxidized mottles; and, in older soils, the topsoil has become acid. These changes are most pronounced in areas distant from active river channels. Young floodplain soils are mainly gray and have developed soil characteristics to depths of about 30–75 cm. Old floodplain soils often have dark gray topsoils and have developed structure to depths of 75–100 cm or more, and the relief often has been smoothed by the wash of fine sediments from ridges towards basins during heavy rainfall occurring when the soils are not flooded. Appendix I gives a more detailed account of the processes of soil development in Bangladesh.

1.4.2 Floodplain Soil Fertility

Bangladesh's floodplain soils are generally considered to be fertile. They have sustained the production of two or three crops a year for many decades, or even centuries, with only moderate or low additions of manures or fertilizers. Popularly, the maintenance of their fertility is attributed to additions of alluvial silt from the annual floods.

Field evidence from the above-referenced soil surveys threw doubt on this popular belief (FAO 1971). Large areas of floodplain land were found to be flooded by rainwater, not by silty river water. Such areas have soils with well-developed profiles, as described above, and strongly acidic topsoils that show no evidence that they receive regular or periodic increments of river sediments. Yet floodplain soils clearly are "fertile," whether flooded by river water or by rainwater. What are the sources of this fertility in areas that apparently do not receive regular increments of new alluvium?

There appear to be four possible sources of plant nutrients in floodplain soils in addition to those that may be provided by new sediment deposits (Brammer 1995b):

- the provision of nitrogen by blue-green algae (BGA) living on the soils and in the floodwater;
- decomposition of leaves and other plant remains, including submerged lower leaves of paddy, jute, and weeds;
- release of nutrients from weatherable minerals in the seasonally flooded topsoils, some of which are dissolved in the floodwater and transferred to other sites; and
- increased availability of phosphorus when topsoils are submerged.

The two latter phenomena are associated with cyclical chemical changes occurring in seasonally flooded soils. When submerged, topsoils become anaerobic (lacking oxygen), under which conditions iron is reduced (in the ferrous form) and the reaction becomes neutral. When air reenters the topsoil after flooding ends, iron is oxidized to the ferric form, and the reaction changes to acidic or alkaline according to the specific type of soil.

Studies by the International Rice Research Institute (IRRI) show that blue-green algae growing in paddy fields may contribute an average of 30 kg/ha of nitrogen per crop season (Roger & Kulasooriya 1980). Studies made in deep-water paddy areas in Bangladesh (including parts of the Jamuna floodplain) suggested annual figures of 8–18 kg/ha of nitrogen fixation (Catling 1993). That is equivalent to 13–30 kg/ha of urea, the usual nitrogenous fertilizer used in Bangladesh.

Catling (*op. cit.*) suggested that those relatively low nitrogen figures could result from the low light intensities within dense stands of deep-water paddy. He stated that, in neighboring fallow fields, algal growth was 20 times greater and possibly producing two to three times as much nitrogen. This observation suggests that levels of algal growth and nitrogen production could be low in silty floodwater through which less light penetrates than in clear water. It also suggests that the change from *aus* and deep-water *aman* paddy cultivation to irrigated *boro* paddy cultivation in recent decades, leaving soils fallow in the *kharif* season, could have increased algal growth and nitrogen release significantly over the levels previously experienced under traditional *kharif* cropping patterns on moderately deeply and deeply flooded land. (*Aus* and *aman* paddy varieties are grown in the *kharif* [rainy] season and *boro* paddy in the *rabi* [dry] season. *Aman* is divided into deep-water *aman,* sown before the rainy season, able to lengthen its stems as floodwater rises, and harvested after floodwater recedes; and so-called transplanted *aman,* planted in the rainy season on shallowly or non-flooded land and harvested after the end of the rains.)

Rother et al. (1988), investigating BGA nitrogen fixation at their Manikganj study site on the Jamuna floodplain west of Dhaka, confirmed Catling's finding that BGA were much more abundant in flooded fallow fields than in flooded paddy fields. However, they also found that twice as much nitrogen was fixed in the pre-flooding period as during the flood period. They estimated that BGA on soils contributed about 11 percent of the nitrogen requirements of deep-water paddy, and soluble nitrogen in floodwater contributed about 6 percent.

In a study of the contribution of flood sediments and BGA to soil fertility carried out inside and outside the Chandpur Irrigation Project on the Meghna river floodplain and the Old Meghna estuarine floodplain, ISPAN (1993) reported that river-derived sediments were mainly deposited close to the river Meghna. Those sediments had higher contents of organic matter, calcium, potash, sulphur, and manganese than local soils, but lower contents of copper and zinc. The quantities of sediments deposited in the year of study (1992, which was a low-flood year) were not reported. Total dissolved solids (TDS) were reported to be high in Meghna water, but levels of calcium, magnesium, potassium, and ammonia nitrogen were moderate or low, and their contribution to plant nutrition was considered to be low relative to that provided by the sediments deposited.

The same study reported that quantities of BGA varied between sites, but were generally considered to be high. They were much more abundant in clear water along the Dakatia River than in turbid Meghna River water, and were slightly higher outside embankments than inside. The amounts of nitrogen fixed were not determined, but it was suggested that they might be about 16–20 kg/ha.

Chapter 2

STUDY SETTING

2.1 Overview of Floodplain Characteristics

2.1.1 Physiography and Relief

The floodplains that cover about 80 percent of Bangladesh are diverse and complex in relief and soils. The 23 floodplain physiographic units recognized (Figure 2.1) are of four kinds:

- *River floodplains* include those of the Ganges, Brahmaputra-Jamuna, and Meghna rivers, their tributaries and distributaries, and some smaller rivers in the east.
- *Piedmont plains* (alluvial fans) occur at the foot of the Himalayas and the northern and eastern hills.
- *Estuarine floodplains* occupy a large area of eastern Bangladesh.
- *Tidal floodplains* are found in the southwest and parts of the southeast (included in the Chittagong Coastal Plain).

Significant differences in physiography, sediments, soils, and flooding characteristics exist between these different kinds of floodplain (FAO 1988).

The rivers traversing these floodplains have changed course over time, leaving behind them an intricate landscape of ridges (former levees) and depressions (interridge depressions, old channels, and backswamps). Elevation differences between ridges and their adjoining depressions are greatest in the Sylhet Basin, where they range up to 5 meters. On other river floodplains and on piedmont plains, differences are in the 2-to-3-meter range, and on estuarine and tidal floodplains elevation differences are 1 to 2 meters or less.

2.1.2 Flooding

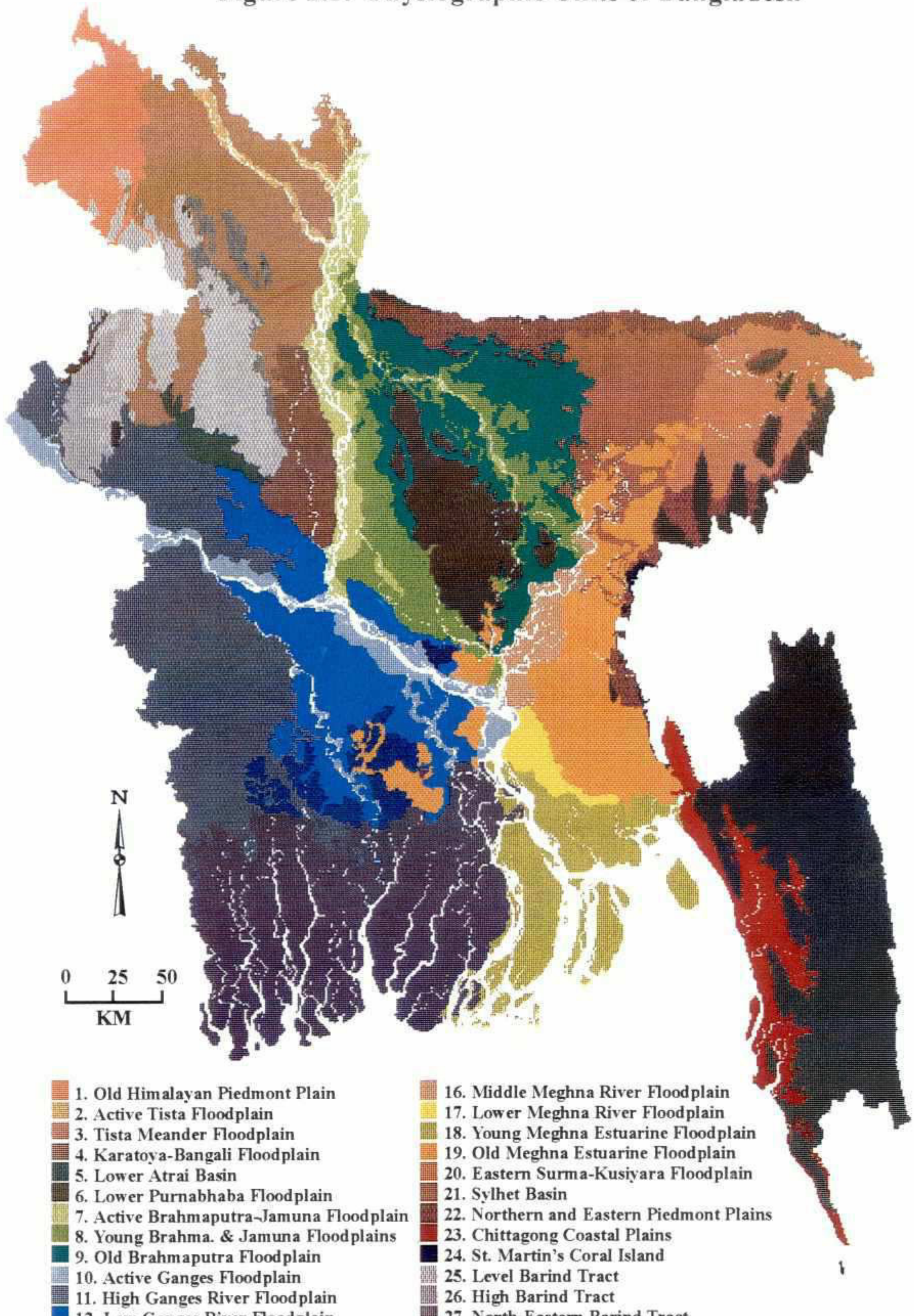
Much of the floodplain area of Bangladesh is inundated during the monsoon season. Flooding generally is shallow in the north and near the coast, and deeper in central Bangladesh and the Sylhet Basin. On ridges, flooding is intermittent or shallow, and it becomes deeper and more prolonged in adjoining depressions; some depressions stay submerged throughout the year. The depth and duration of flooding vary from year to year, depending on the amount of floodwater flowing in from India through the main rivers and on the amount and intensity of local rainfall. Regional and local differences in flood depth and duration are important determinants of the cropping patterns in Bangladesh that will be described in Section 2.2.7.

2.1.3 Age

Three landscape ages can generally be recognized on river floodplains:

- *Active floodplains,* within and alongside rivers, have shifting channels that are liable to deposit and erode sediments during the annual floods.
- *Young floodplains* are stable land that a river or its distributaries have recently moved away from (within 50–200 years on the Jamuna floodplain) and that has developed predominantly gray topsoils and subsoils.

Figure 2.1: Physiographic Units of Bangladesh



- *Old floodplains* have remained stable for a long period (possibly centuries) and have developed mature, dark-colored topsoils and well-oxidized subsoils.

Piedmont and estuarine floodplains also have young and old landscapes. The high (moribund) Ganges river floodplain, Old Brahmaputra floodplain, Old Meghna estuarine floodplain, and Old Himalayan piedmont plain, for instance, may be several hundred to several thousand years old. The topsoil of an Old Meghna estuarine floodplain buried by a Ganges river floodplain soil southeast of the Gopalganj-Khulna *Beels* has a radiocarbon age of ca. 1,800 years; and a buried layer within the Old Meghna sediments is ca. 3,000 years old (FAO 1971).

The map in Figure 2.2 shows floodplains of different ages. It should be noted that the ages in the map are relative rather than absolute and have been derived by considering the physiographic units of Bangladesh shown in Figure 2.1. Also, narrow belts of active and/or young floodplains adjoining small rivers crossing young and old floodplains cannot be shown on the scale of the figure.

2.1.4 Subsidence

The sediments underlying Bangladesh are several hundred to several thousand meters thick (Khan 1992). They apparently occupy one or more geosynclinal or fault troughs between the Indian massif to the west and the folded Yoma-Arakan hill ranges to the east. It is difficult to determine whether subsidence still continues in these troughs. This is due in part to the paucity of datable horizons, but it is also because sea-level fluctuations occurred during the Pleistocene and Recent periods. The comparatively small changes in Bangladesh's coastline since Rennell's maps were made in the 1760s suggest that outgrowth of the Ganges-Brahmaputra-Meghna delta by sediment deposition has been counteracted by subsidence, which could be due to tectonic warping or to compaction of the underlying sediments, or both (Eysink 1983).

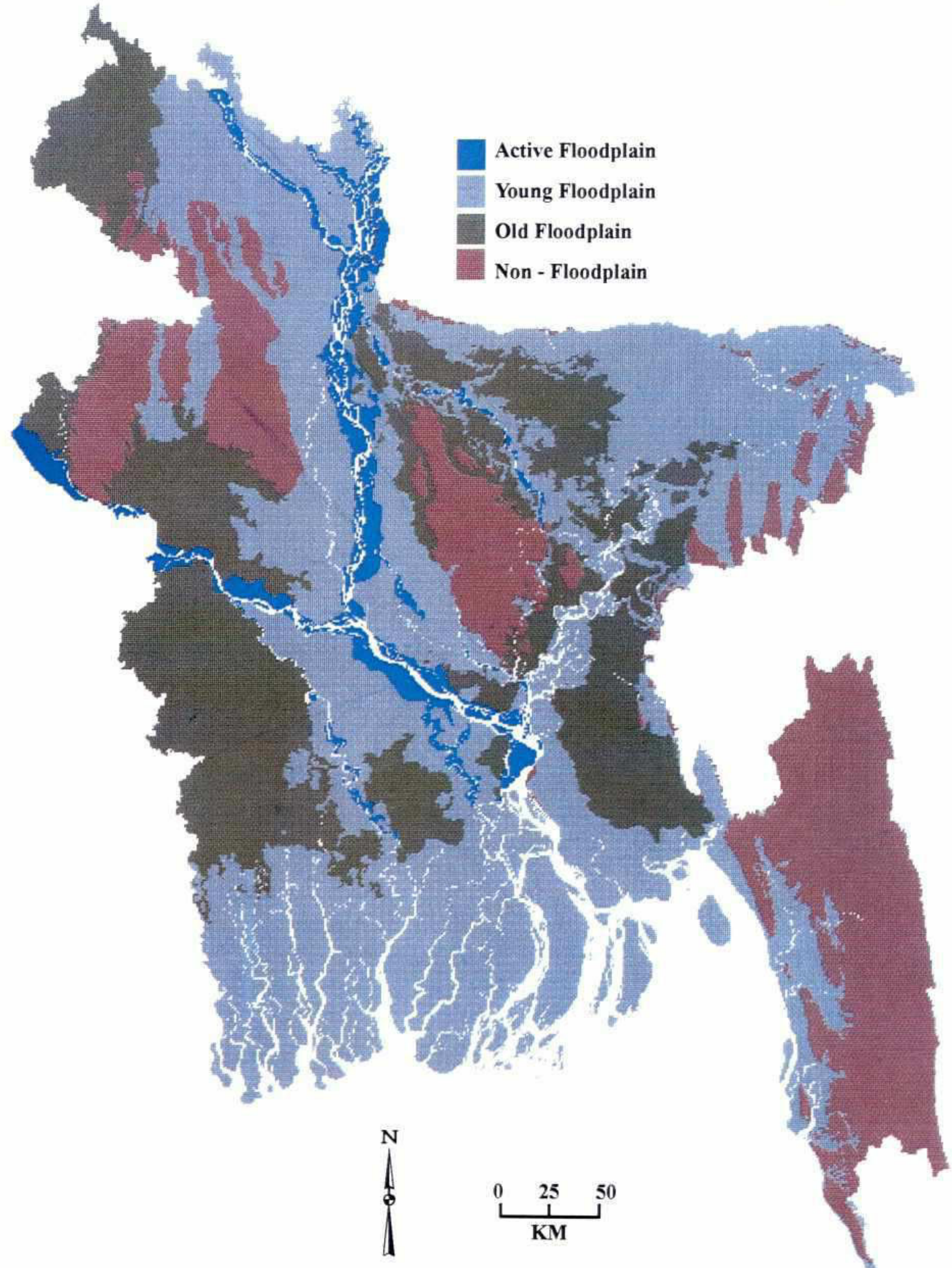
However, subsidence rates in the delta are neither uniform nor universal. They probably are high (1–2 cm/year), for example, in the Sylhet Basin. Recent subsidence is also suggested by the down-warping of Madhupur Tract relief and soils below Old Meghna estuarine sediments and soils east of Dhaka, and of Barind Tract relief and soils below Atrai sediments and soils in the Lower Atrai Basin. On the other hand, the western edges of the Madhupur and Barind tracts have been uplifted, and the western part of the high (moribund) Ganges river floodplain and the southeastern part of the Old Meghna estuarine floodplain also stand higher than adjoining parts of their floodplains, implying that these delta-margin areas may also have been uplifted.

Between Dhaka and Narayanganj there is an organic layer, formed in mangrove swamps growing at about sea level, buried in tidal clays 1–2 meters below present sea level. The radiocarbon ages of this layer range from 5,600 to 6,700 years. Other peat layers buried less than a meter deep in and to the south and east of the Gopalganj-Khulna *Beels* date from between 800 and 3,000 years ago (FAO 1971). These dates suggest that any subsidence occurring in this central-southern area has been very slow.

2.2 The Study Area

The study area, which is shown in Figure 3.4, spans parts of the Jamuna and Old Brahmaputra floodplains (Figure 2.2). These floodplains together cover 16,344 km² (about 11 percent of the country). The study area is bounded on the west by the Jamuna left bank, on the east by the Madhupur Tract, and extends from the Chatal and Jhenai river systems in the north to the Elangjani and Lohajong rivers in the south. The following sections briefly describe the physical and land use characteristics of these floodplains. The Tangail and Jamalpur reconnaissance soil survey reports (SRDI 1967a,b) and the AEZ report (FAO 1988) contain more complete descriptions.

Figure 2.2: Relative Age of Bangladesh Floodplains



2.2.1 Climate

The study area has a tropical monsoon climate. Mean annual rainfall, most of which occurs between May and September, is about 1,500 mm in the south and 2,000 mm in the north. Rainfall amounts vary appreciably between years. Minimum and maximum daily temperatures range between about 10–14° and 25–27°C in winter (December–February) and between about 25° and 32°C in the monsoon season (June–September). The highest temperatures, often exceeding 35°C, occur in the pre-monsoon months (April–May). Mean monthly potential evapotranspiration rates exceed rainfall between November and March but are below mean rainfall in other months.

2.2.2 Physiography

As shown in Figure 2.2, the Jamuna floodplain has three subunits: the active, young, and older floodplains. These subunits, as described below, differ from each other in the relative maturity of their relief and soils. The boundaries between them are sometimes sharp, as is the case between the Young and Older Jamuna floodplains at Sharishabari. Elsewhere they can be indistinct: for example, in some transitional areas, very young floodplain land is found within the active floodplain. In other areas, recent, small spills of new alluvium have penetrated areas of young or older floodplain on scales too small to show in the figure. A part of the Old Brahmaputra floodplain in the east has been buried by sediments and soils of the Older Jamuna floodplain.

2.2.3 Floodplain Development

The alluvial sediments in the study area belong to the Brahmaputra-Jamuna system. Those of the Old Brahmaputra floodplain were laid down when the river occupied a former course (presently that of the Old Brahmaputra River) running north and east

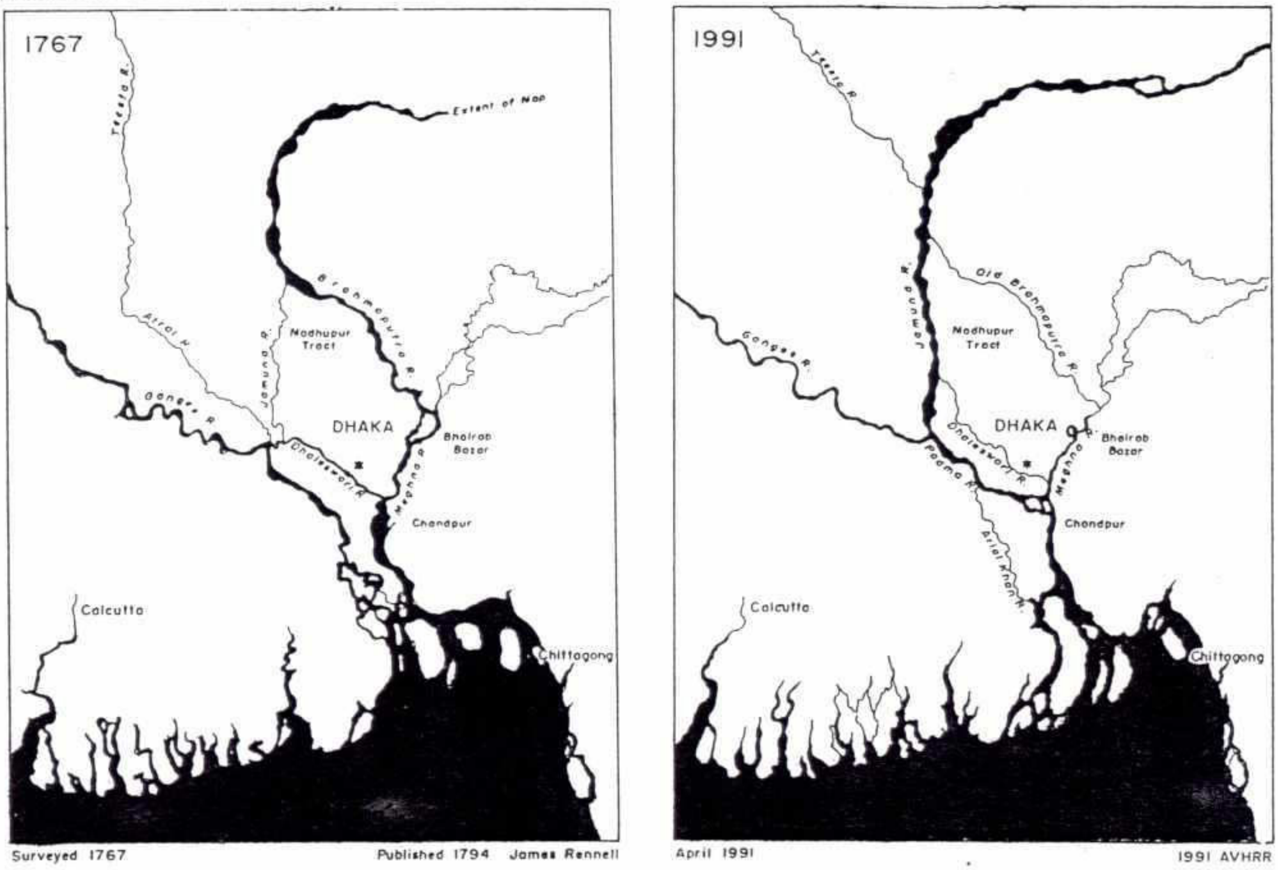


Figure 2.3 River Systems of Bangladesh: 1767 and 1991

of the Madhupur Tract (Figure 2.3). Between 1782 and 1830, the Brahmaputra shifted its course to the west of the Madhupur Tract. This reach of the river, now called the Jamuna, flows immediately west of Dewanganj, Madarganj, and Sharishabari. Since its change of course, the Jamuna channel has tended to widen and move progressively westward, leaving a broad floodplain on its eastern side (the Jamuna floodplain). On its western side, the river is continuously cutting into an older floodplain (the Teesta and Karatoya-Bangali floodplains).

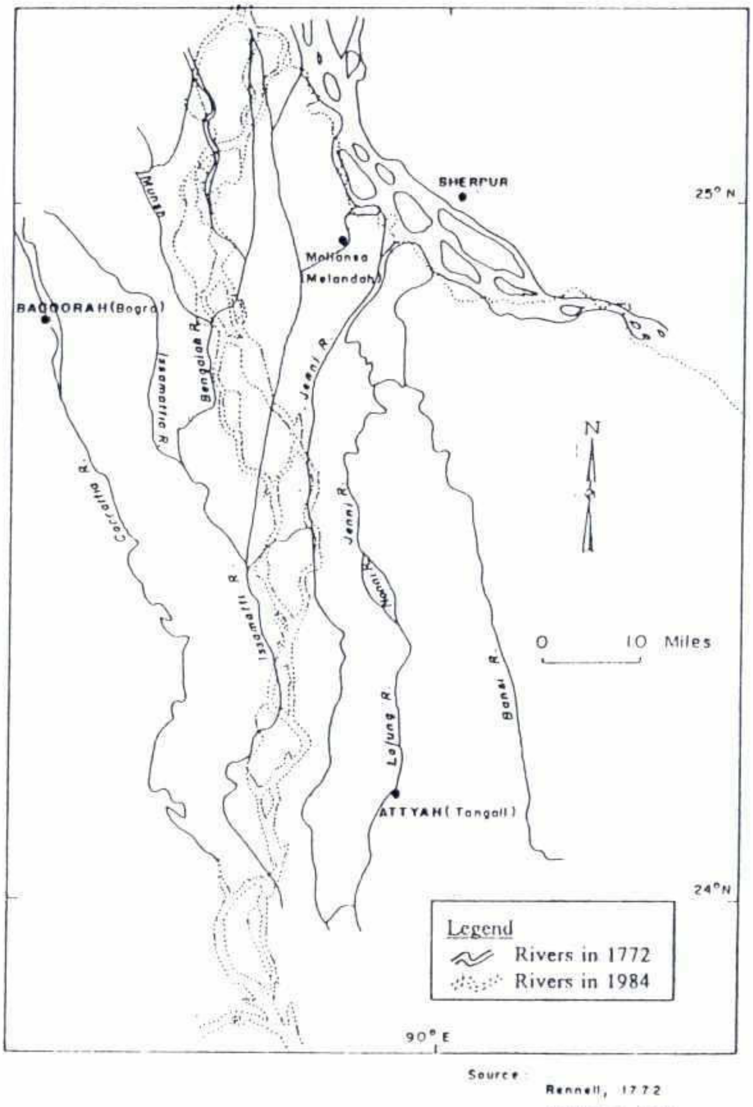


Figure 2.4 **Changes in a Part of the Brahmaputra-Jamuna River System, 1772 and 1984**

The Jamuna floodplain is crossed by a number of distributary channels (offtakes) flowing southward or southeastward away from the main channel. Most of these channels, which appear on the Rennell map of 1772 (Figure 2.4), are now partially or wholly choked by sediments, and they apparently carry much less flow now than in the past. Flow in the Dhaleswari River south of the study area has also decreased considerably in the past 20–30 years, suggesting a general trend for Jamuna distributaries to die out progressively downstream. A similar trend is apparent on the Ganges floodplain. The cause(s) of this deserve investigation in future studies.

No such trend is discernible on the Brahmaputra-Jamuna west bank. There, rivers on the Teesta and Karatoya-Bangali floodplains flow towards or parallel with the Jamuna (though the threatened breakthrough of the Jamuna into the Bangali River north of Sirajganj would create a distributary channel on this bank if it occurred). Several old channels of the Teesta and its distributaries occur on the Teesta floodplain, which is an alluvial fan, but these channels do not appear to have progressively silted up downstream. The Teesta shifted from a western channel down the Atrai into its present course along the northern edge of its floodplain about 200 years ago.

The section of the Jamuna River adjacent to the study area, has a braided channel up to approximately 15 km wide. Within and alongside its course, the constantly shifting secondary and tertiary channels deposit and erode considerable areas of land each year. This belt is the Active Jamuna floodplain. As the river has moved progressively westward, it has abandoned areas of active floodplain land, which have become less exposed to the risks of bank erosion and burial by new sediments. This stable land constitutes the mainland part of the Jamuna floodplain.

That floodplain has two subdivisions: the Young Jamuna floodplain, with rather irregular relief and relatively young soils; and the Older Jamuna floodplain, with smoother relief and more developed soils. The young floodplain apparently is still exposed to occasional flooding with silty river water from the Jamuna or its distributaries. This happens less frequently on the older floodplain. Due to the ongoing westward shift of the Jamuna River, the boundary between the active and young floodplains is constantly changing.

Sediments of the Older Jamuna floodplain have buried parts of the Old Brahmaputra floodplain in the east. It is by no means certain that all these Older Jamuna sediments were laid down since the Brahmaputra changed course. The fact that the Jhenai River (shown in Figure 2.4) still follows virtually the same course that it occupied in Rennell's day suggests that these deposits probably were laid down mainly by that river before the Brahmaputra changed into the Jamuna channel. Unfortunately, radiocarbon dates are not available for the Old Brahmaputra floodplain topsoils underlying these sediments.

The Old Brahmaputra floodplain has smooth relief and more mature soils than the Jamuna floodplain. Rivers crossing this floodplain in the study area mainly carry local runoff water, not Brahmaputra-Jamuna river water. The Bansi River, which apparently carried these sediments into the area, is now cut off from the Old Brahmaputra, but a connection is shown on Rennell's map.

2.2.4 Geomorphology

Floodplain landscapes are rarely flat. Both active and older floodplains usually have a succession of ridges and depressions. This is because river sediments generally are laid down irregularly in location and time. In the study area, there are four main relief types (Figure 2.5).

Braid bar, meander scroll, and dune patterns occupy parts of the Active Jamuna floodplain where sediments have been deposited on the channel margins by rapid and turbulent river flow during flood stages. (Small areas of active floodplains occur along distributary rivers crossing the Jamuna and Old Brahmaputra floodplains.) Braid bars and meander scrolls are narrow, arcuate or linear ridges and interridge depressions formed by lateral migration of the river channel. Dune (or mega-ripple) fields are intricate areas of irregular-shaped ridges and hollows formed by bedform migration on the channel margin bottom. In both patterns, differences in elevation between ridge tops and adjoining depression centers usually are 1–2 meters over distances of about 10–50 meters. The sediments may be predominantly sandy or silty, but they are generally in alternating sand and silt layers of varying thickness. Meander scar patterns sometime remain visible on young and older floodplains unburied by later sediment deposits.

River levees are found along sections of main river channels and interior rivers and *khals* on parts of the active and young floodplains. Natural levees are formed by rapid deposition of sediment near the channel during overbank flow. As in the grain size relationship in crevasse splays, deposition rates decrease exponentially due to a reduced capacity for sediment transport as flow velocities decrease away from the channel. Levees form a relatively high riverbank that slopes gently outward to a neighboring depression (flood basin). The relief can be slightly irregular in places, but generally is smoother than where splays occur. The height difference between the riverbank and the adjoining depression can be about 1 meter over a distance of less than 100 meters along small *khals,* and up to 2–3 meters over 500 meters or more alongside major river channels.

Levee deposits tend to be sandy or coarse-silty near the riverbank, becoming finer-textured away from the river. They often include layers of different texture, representing deposits made by floodwaters of different height or velocity. These layers, including the surface layer, often are finer near the top

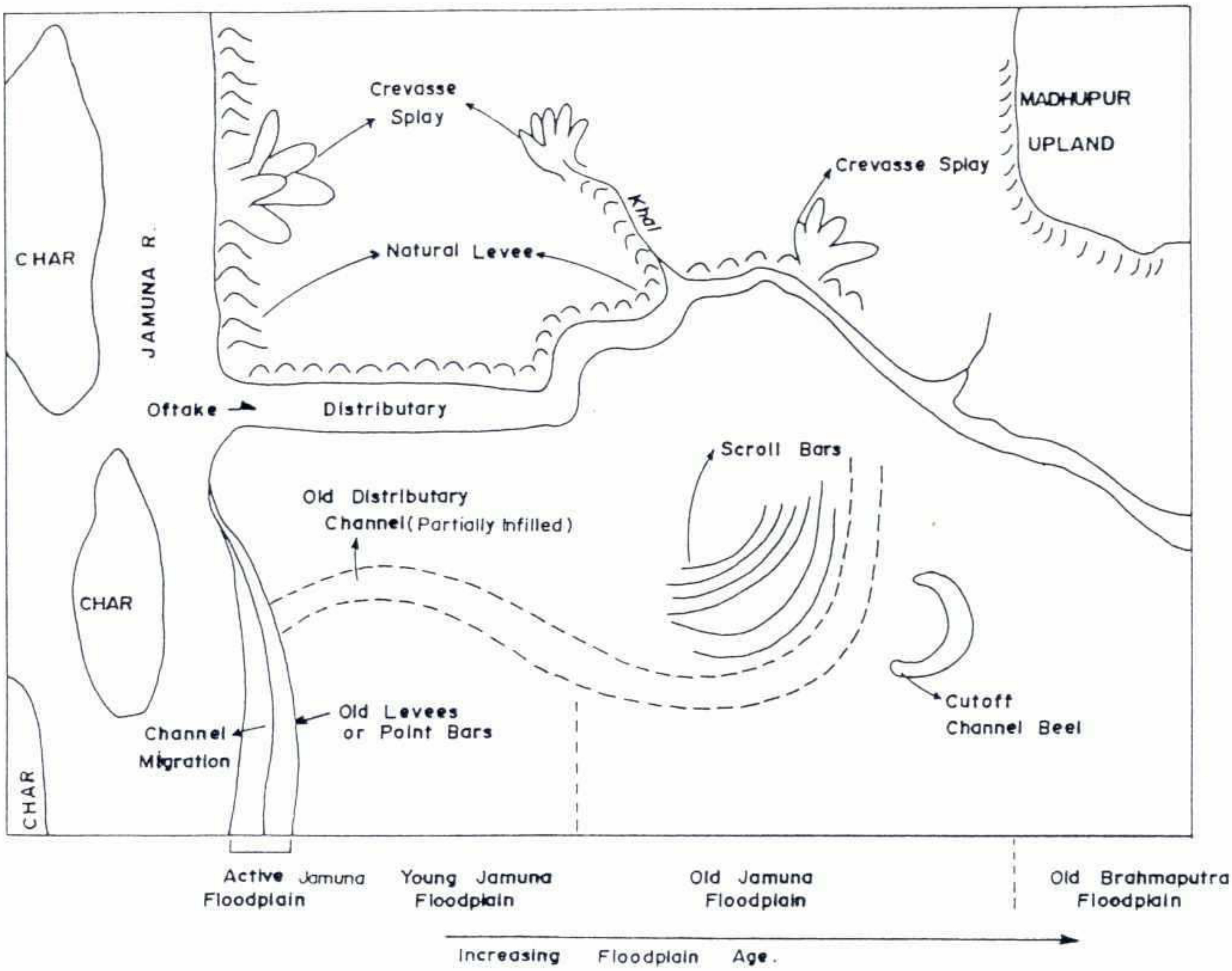


Figure 2.5 Representative Landforms in the Brahmaputra-Jamuna Floodplain

than lower down. They overlie former riverbed or splay deposits, so their base (which often forms the base of the soils that develop in them) often is irregular in depth.

Crevasse splays mainly form on land adjoining large river and distributary channels on the Active and Young Jamuna floodplains. They develop in places where rising flood levels in a channel overtop the bank along a limited section. This allows river water to flow rapidly and turbulently onto adjoining land that was not flooded, or was only shallowly flooded, when the river "burst its banks" (the natural levee is breached). Splay deposits, as the name implies, are like finger deltas, with narrow ridges and interridge depressions spreading out from the breach site to form a more or less arcuate fan. Similar irregular splays sometimes occur in basins of the Young and Older Jamuna floodplains where rapidly rising floodwater has entered along *khals* (small, natural or artificial channels) when water levels in the basin were lower than in the adjoining river. Sediments tend to be sandy on the higher parts of splays and more silty on lower parts. This is due to decreasing flow competence with distance from the channel for carrying sediment in suspension and as bedload.

Flood basins are nearly enclosed depressions between the levees of neighboring rivers. On the active floodplain (mainly in areas of very young floodplain), basins lie between neighboring channels. On older floodplain land, basins lie between the main river and a distributary river or between neighboring distributary rivers. These basins usually drain through small *khals* on the downstream side. Subsidiary levees or crevasse splays sometimes occur along such *khals* where the latter also serve to admit water to basins on rising flood stages. For that reason, the relief in basins on the Young Jamuna floodplain is not always smooth. Flood basins contain clayey silts and silty clay deposits that settle out distant from the channel. Permanently flooded areas in some old floodplain basins (*beels* and *haors*) contain peat accumulations.

Ridge-and-basin relief mainly occurs on the Older Jamuna floodplain and the Old Brahmaputra floodplain. In these areas, an initially rather irregular relief has been smoothed out by a combination of processes: by deposition of finer levee sediments in slow-moving floodwater behind riverbanks; and by lateral wash of sediments from ridges towards depressions during heavy rainfall when part or all of the relief is not flooded. The ridges are the levees of former river channels that have silted up. Clay deposits in basins on old floodplains can be 0.5–1 m or more thick. Both ridge and basin deposits often have an irregular boundary with underlying former levee and riverbed deposits. Elevation differences between ridge tops and basin centers generally are 2–3 meters over distances of 0.5-1 km.

Floodplain gradient. In addition to local relief differences, there is an overall gradient from north to south or southeast on the Jamuna and Old Brahmaputra floodplains. This gradient is steeper, in fact, than that of the Jamuna River itself. As will be described below, this is indicated by an increase in the depth of seasonal flooding on floodplain land from north to south (which continues into the Jamuna floodplain south of the study area).

The reason for this steeper gradient, especially on the Old Brahmaputra floodplain, remains to be established. Possible causes include:

- uplifting of the northern part of Bangladesh by tectonic activity in the 1782 and 1897 earthquakes, which seems to have affected northern areas more than southern ones;
- subsidence of southern and central parts of Bangladesh, either by tectonic movement or by compaction of the underlying sediments, as discussed in Section 2.1.4;
- progressive aggradation by river sediments over former tidal and estuarine lowlands in central and southern Bangladesh; or
- a combination of these factors.

2.2.5 Soils

The soils of the study area change from west to east, from stratified alluvium on the Active Jamuna floodplain to soils with well-developed profiles on the Older Jamuna and Old Brahmaputra floodplains. Figure 2.6 indicates the progressive stages in soil development on these floodplains, and Appendix I describes the soil-forming processes involved. The main features of the soils in each physiographic unit and subunit are described below. Profile descriptions and laboratory data for the main soils are in Appendix II.

The Active Jamuna floodplain has stratified sands and silts on an irregular relief of linear ridges and interridge depressions. The sediments usually are more sandy on the ridges and more silty in the depressions, but larger, more uniform areas of sand or silt sometimes occur after major floods. These sediments are subject to burial by variable amounts of new sediments during annual floods, which may alter the relief and surface texture between years. They are also exposed to removal by bank erosion as channels shift or widen.

Such sediments generally are gray, stained yellow or brown along cracks to varying degrees, and often still raw and unripened in silty layers. They are neutral to moderately alkaline in reaction. The description and laboratory data for Silty Jamuna Alluvium (profile 19 in Appendix II) illustrate the

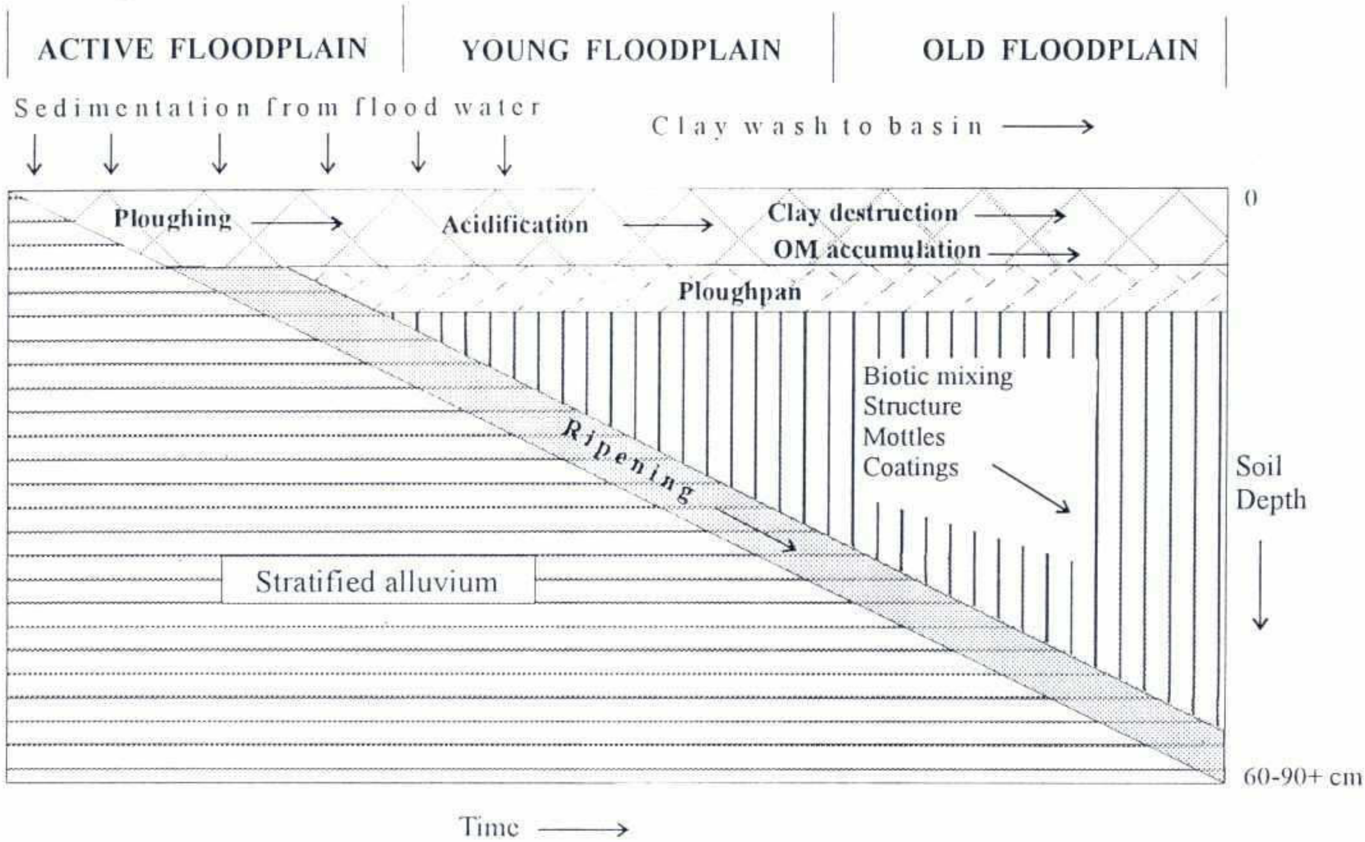


Figure 2.6 Stages of Floodplain Soil Formation in Bangladesh

physical and chemical properties of Active Jamuna floodplain sediments and soils.

The Young Jamuna floodplain occupies a broad band adjoining the active floodplain. On the evidence of topographic and soil maps, young floodplain land has remained stable (i.e., not been affected by bank erosion or burial by thick layers of sediments) for 50 years or more. However, the relief and soils are still relatively young. An irregular pattern of ridges and interridge depressions occurs within a broad ridge-and-basin landscape, and the soils have profiles in which stratification has been broken up and soil characteristics developed to a depth of about 30–50 cm overlying stratified alluvium. The rapidity of soil formation was noted in field studies of the Sharishabari block which had changed from active floodplain when mapped in 1965 to young floodplain when visited in 1994.

Generally, except in relatively sandy materials, stratification has been completely broken up in the subsoil, and structure, coatings, and mottles have developed. However, some areas of less-developed soils exist on recent spill deposits adjoining internal channels, and also on sandy ridges and in perennially wet depression centers where soil development is slow. The developed soils range from gray or olive silt loams on the ridge tops to gray silty clay loams on lower ridge sites and basin margins, and to gray silty clays in depressions.

The descriptions and laboratory data for the Sonatala and Dhamrai series (profiles 16 and 17 in Appendix II) illustrate the physical and chemical

Table 2.1 Depth-of-Flooding Land Types

AEZ	Normal Maximum Water Depth (cm)	MPO
Highland	0	F0
Medium Highland-1	0–30	F0
Medium Highland-2	30–90	F1
Medium Lowland	90–180	F2
Lowland	180–300 (flooded <9 months)	F3
	180–300 (flooded >9 months)	F4
Very Low Land	>300	F4
Bottomland	Mainly >300, but includes perennially wet land in other classes	F4

Note: This classification was developed on the country's reconnaissance soil surveys and in the agroecological zones (AEZ) study (FAO 1988). The Master Plan Organization (MPO 1987) adopted the system with some modifications, including an increase of the F3 land type depth of flood to 360 cm.

carries sediments into adjoining depressions. All such changes in land elevation due to sedimentation are rapid relative to changes due to land subsidence that may be occurring, and they will tend to obscure them, except possibly in the case of earthquakes (for a graphic account of the effects of the 1897 earthquake on land levels and sediments on the neighboring Teesta floodplain, see Khan 1977). Constructing flood embankments can also reduce flood levels on the land side (and possibly increase them on the river side), and road and railway embankments can impede the flow of water across a floodplain, causing changes in normal flooding characteristics.

Not all floodplain land is regularly flooded by river water. Such inundation mainly occurs on active floodplains and adjoining parts of the young floodplain. In years with exceptionally high floods, such as 1988, river water may extend over most or all of the Jamuna floodplain, but soil profile evidence suggests that river water rarely, if ever, extends over the Old Brahmaputra floodplain. This can be substantiated by comparing the satellite image of the 1987 flood (Figure 3.9) and the physiographic map of the study area (Figure 3.10). The satellite image shows only isolated areas of sediment-laden floodwater. The characteristic dark-colored topsoils on this floodplain have not been buried by gray Jamuna sediments, as they have in the eastern part of the Older Jamuna floodplain.

Many areas not flooded by river water are flooded by non-turbid rainwater. This water comes from two sources. One is runoff of rainfall into basins which is then ponded on the land when high river levels block drainage from the area. The other is groundwater that rises above the surface in depressions during the monsoon season. The extent of rainwater flooding varies within the monsoon season and between years according to the amount and intensity of local rainfall and according to external river levels.

Flood embankments constructed over the past 20 to 30 years apparently have reduced the extent of

Table 2.2 Land Type Distribution in the Sharishabari and Kalihati Blocks

	Percent Distribution of Land Types			
Study Block	Highland	Medium Highland	Medium Lowland	Lowland
Sharishabari	0	51	42	7
Kalihati	13	58	23	6

properties of Young Jamuna floodplain soils. The fact that the topsoils in all these profiles are near-neutral in reaction suggests that they are still receiving sufficient new alluvium during seasonal flooding to counteract the acidification that occurs in older floodplain soils.

The Older Jamuna floodplain generally has a smooth ridge-and-basin landscape with more mature soils than are found on the younger floodplains. Near its eastern edge it overlaps the Old Brahmaputra floodplain, the characteristic soils of which can often be found buried below Jamuna soils and sediments. The soil series developed on the Older Jamuna floodplain are similar to those on the younger floodplain, with a similar range in texture from silt loams on ridge tops to silty clays in depressions, but their profiles are usually more deeply developed, and structure, coatings, and mottles are more strongly expressed. Older Jamuna floodplain soils differ from Old Brahmaputra soils in having gray instead of dark gray subsoil coatings; topsoils also usually are gray, not dark gray.

The descriptions and laboratory data for the Dhamrai and Sabhar Bazar series (profiles 21 and 12) illustrate the physical and chemical properties of Older Jamuna floodplain soils. Note that both these profiles have moderately acid topsoils and higher organic matter contents than the profiles described on younger floodplains.

The Old Brahmaputra floodplain in the east and north of the study area has a smooth landscape of ridges and basins with more mature soils than occur on the Jamuna floodplain. These soils range from silt loams on ridge tops to heavy clays in depression centers. They are characterized by dark gray topsoils and subsoil coatings, and by brighter subsoil oxidation colors than occur in Jamuna floodplain soils. Many basin centers stay wet for most or all of the dry season.

The description and laboratory data for the Ghatail series in Appendix II illustrate the physical and chemical properties of basin soils on the Old Brahmaputra floodplain. Note the higher organic matter content and stronger topsoil acidity than in equivalent basin soils on the various ages of Jamuna floodplain. There also is a greater contrast between topsoil and subsoil textures, reflecting clay destruction in the topsoil under seasonally reduced and oxidized conditions (see Appendix I).

2.2.6 Flooding

Floodplain landscapes are subject to flooding during the monsoon season. Soil survey findings indicate that the highest ridge sites are submerged for brief periods and only in years with high floods. Lower ridges and depressions are flooded in most years or every year. Some depression centers stay under water throughout the year. There is an overall trend for depths of flooding to increase from north to south or southeast across the study area (see Figure 3.11).

The depth and duration of seasonal flooding are critically important for agriculture, as will be described in Section 2.2.7. Bangladeshi farmers classify their land according to the "normal" depth of flooding: i.e., what they expect in years with average floods (possibly in three or four years out of five) according to local experience. These flooding characteristics determine their annual cropping patterns. Table 2.1 shows a standardized form of this classification developed on soil surveys in the 1960s, together with a modification developed for HYV paddy cultivation by the Master Plan Organization (MPO, now the Water Resources Planning Organization, WARPO). Table 2.2 shows the relative proportions of land in each flood-depth type for the two study blocks. (The distribution of these depth-of-flooding land types in the Sharishabari and Kalihati blocks, as surveyed under this study in 1994, is shown in Figure 4.2.)

Flooding characteristics can change over time. This can happen when continuing sedimentation gradually builds up land levels in relation to flood levels: e.g., on active floodplains; on older floodplains where thick spill deposits bury land in depressions formerly subject to deep flooding; and, over a longer time scale, where runoff from ridge soils

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river flooding on the Jamuna floodplain in "normal" flood years. However, river flooding can still occur on flood-protected land in years with high floods, when more river water flows down distributary channels and through regulators in the embankment, or when the embankment is breached, as happened both alongside and upstream of the study area in 1988.

2.2.7 Land Use

The soils of the study area are intensively used for agricultural production. In most places, farmers grow two or more crops per year, an average cropping intensity of more than 200 percent. The main determinants of cropping patterns are climate, soil and land type, risk of flood damage, and the availability or unavailability of irrigation. The Bengali names of crop seasons and paddy crops used below are defined in Section 1.4.2.

Rain-fed crops are most extensive on the Active and Young Jamuna floodplains, but they also are grown on non-irrigated parts of older floodplains. On Highland and Medium Highland soils, the main cropping pattern is *aus* paddy or jute in the *kharif* season followed by a dryland *rabi* crop. Some land is used for a single crop of sugarcane, and some is triple-cropped with jute, transplanted *aman,* and either wheat or potatoes. On Medium Lowland soils, mixed *aus* and *aman* paddy are grown in the *kharif* season and followed by *rabi* pulses or wheat.

Away from the active floodplain much of the land is irrigated in the dry season. Shallow tubewells are the main source of irrigation, but deep tubewells and low-lift pumps also provide some irrigation. With irrigation, farmers grow *boro* paddy in the dry season on all except the most permeable ridge soils and recent spill deposits. On Medium Highland soils, *boro* paddy is followed by transplanted *aman* in the *kharif* season and sometimes also by mustard grown early in the next *rabi* season. On Medium Lowland soils, *boro* is sometimes followed by transplanted deep-water *aman,* and this is sometimes followed by mustard. A single crop of *boro* is grown on Lowland sites. Except in a few wet depression centers, HYV *boro* is grown.

Farmers use fertilizers for all of their major crops. More fertilizers are used for irrigated crops than for rain-fed crops. In both cases, farmers apply more urea than TSP and MP fertilizers. This study observed farmers in many places using urea at higher-than-recommended rates and TSP and MP at far below recommended rates. The crops grown in the study area and typical fertilizer rates used are shown in Tables 4.1a and b

2.2.8 Madhupur Tract

The Madhupur Tract, on the east of the study area and from which several soil and cesium samples were taken for comparative purposes, is an uplifted block of unconsolidated Madhupur Clay, probably of Tertiary age (Huizing 1971). It includes dissected and undissected areas, with both deep and shallow soils, mainly red or brown in color, but including some gray upland and valley soils.

Chapter 3

METHODS

3.1 Floodplain Monitoring

3.1.1 Study Block and Site Selection

The study area (see Figure 3.4) covered a portion of the Jamuna and Old Brahmaputra floodplains. Within and adjacent to this selected area, exploratory visits were made during March 1994 to select appropriate sites for more detailed study. The areas visited were: Dewanganj, Madarganj, and Sharishabari *thanas* of Jamalpur District; Bhuapur and Kalihati *thanas* of Tangail District; and Daulatpur *thana* of Manikganj District. An average of half a day was spent in each *thana* collecting data on the flood regime and sediment deposition, the natural setting, the amount of disturbance to natural conditions by embankments and other structures, and site accessibility.

Based on these exploratory investigations, supported by use of the FAP 19 Geographic Information System (GIS) database and preliminary results of a sedimentation zoning model, two rectangular study blocks were selected for detailed characterization and sampling. One block was in Sharishabari, the other was in Bhuapur and Kalihati *thanas*. The blocks chosen represented the anticipated range in sedimentation zones in each area. The factors used for the selection were: proximity to the Jamuna River and its distributaries; position along the Jamuna River; flood regime; physiography and relief; soil types; and disturbance of natural conditions by roads, embankments, etc. The selection process also took into account the availability of maps and other data, and the accessibility of prospective sampling sites during floods and at other times.

3.1.2 Description of Blocks

Before setting up the sampling program, the study blocks were surveyed in detail. The Sharishabari block was surveyed April 17–21, the Kalihati block between April 27 and May 1. The surveyors used large-scale (1:20,000) aerial photographs, *thana* soil maps, topographical maps, and portable Global Positioning System (GPS) receivers. Based on interpretation of the aerial photos, traverse lines 1 km apart were selected, aligned to cross all the main physiographic units and land types of the study area. At each observation point along the traverse lines, information was collected by direct observation and by interviewing local people. Data were gathered on flood regime, relief position, soil characteristics, infrastructure, cropping patterns, and farmers' observations of the thickness of sediment deposited in average and high-flood years. Maps were prepared in the field to show sedimentation zones, land types, and infrastructure. This information was later added to the GIS database, where it was used to verify and update GIS maps and sedimentation zone modelling, and to select sediment and soil sampling sites.

3.1.3 Sample Site Selection

Within each study block, 10 sample plots measuring approximately 10 × 10 m were selected to represent the major flood and sedimentation regimes identified. Sediment sampling was restricted to the center of each plot to minimize disturbance by humans and animals. Arrangements were made with the landowner to construct a secure fence to keep people and livestock out; the fence was then covered with bamboo matting to keep floating vegetation out. Landowners were financially compensated for keeping the land fallow and undisturbed during the study period. A local person hired for each sampling site ensured that it was not disturbed, and collected floodwater samples and information on inundation depth.

3.1.4 Sediment Sampling

Since there was no established method for sampling flood-borne sediments on Bangladesh's floodplains, the study used three methods to collect representative samples at each of the 20 sampling sites and determine the most suitable method for future studies. The methods used were: soil coring, permeable mats, and sediment traps. Below is detailed information on each of these methods.

Mats and traps were placed at the Sharishabari sites between May 26 and 30, and at the Kalihati sites between June 6 and 10. Six additional sites were selected in low-lying areas close to the river between August 14 and 19. At these sites, permeable cloth mats were placed on land already inundated by river water. These additional sites were necessary because most of the other sites had not been inundated due to very low flood levels in the Jamuna River in 1994. Figure 3.1 shows the layout for each sampling site.

Soil cores. At each site, a thin layer of fine brick dust was spread over the soil surface in three subplots measuring 50 × 50 cm. This was done with the intention of collecting 6-inch cores of sediments deposited on the marker layer, which could then be sent to the laboratory for physical and chemical analysis. However, because of the very low flood, none of the sites received enough sediments to make core sampling feasible, so no samples were collected by this method.

Permeable mats. Permeable jute mats measuring 2 × 2 m were placed near the center of each of the six additional sample plots and secured with iron nails. On each mat, three 50 × 50 cm permeable cloths were secured with iron nails. The sediment samples were collected on September 6–7, after the floodwater had receded. The sediment samples were carefully collected with the smaller cloths and placed in sealable plastic bags for shipment to the

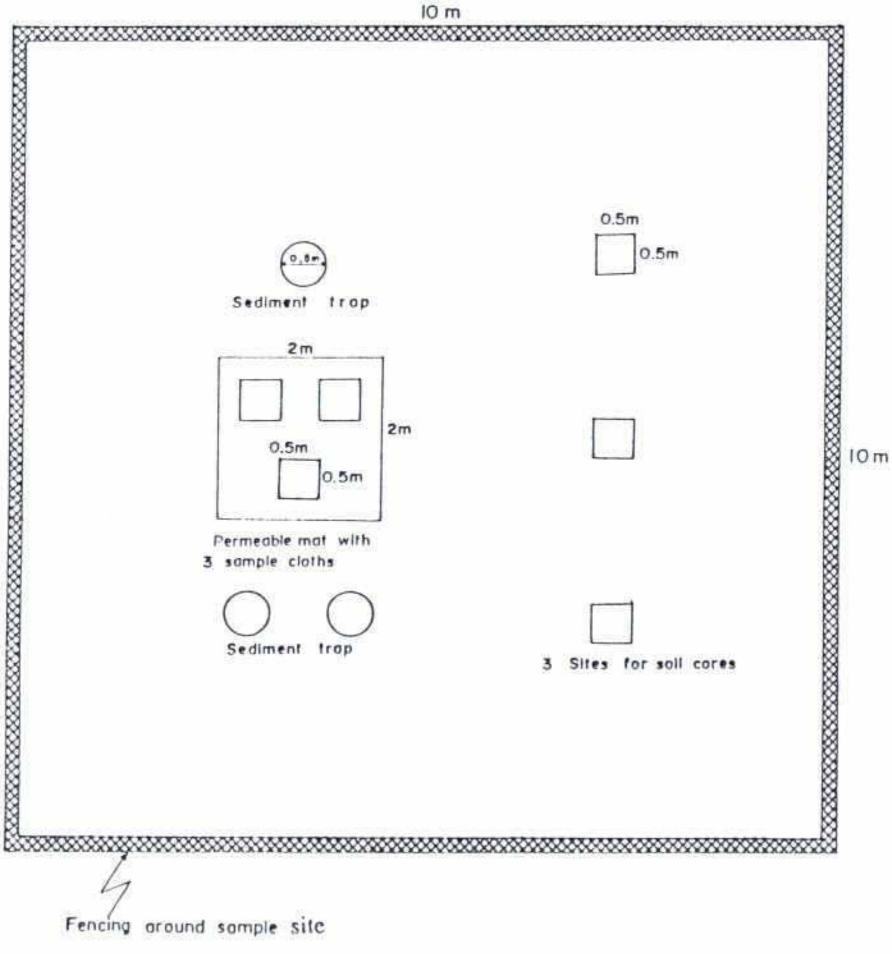


Figure 3.1 Layout of Sample Site

determined on calcium phosphate extracts using a turbidimetric procedure for sulphur and colorimetric measurement for boron. Phosphorus, potassium, iron, manganese, and zinc were determined on sodium EDTA extracts (0.25 N $NaHCO_3$/0.01M EDTA/0.01 N NH_4F with 0.5 g superfloc 127 per 10 liters). Phosphorus was measured colorimetrically, and the other nutrients were measured by atomic absorption spectrophotometry.

BINA followed ASI procedures in measuring water sample nutrients. Dissolved solids were determined following Standard Methods for Analysis for Soils, Plant Tissues, Water and Fertilizers (1990).

The FAP 24 laboratory used the hydrometer method to determine suspended sediments in the water samples. For each sample, data were presented for wash load (<63 micron) and bed load (>63 micron).

3.1.9 Nutrient Balance in Soils

Data on crop uptake of nutrients were based on a compilation made by the Bangladesh Agriculture Research Council (BARC) of the results of field trials conducted by the Bangladesh Agriculture Research Institute (BARI), Bangladesh Rice Research Institute (BRRI), and Bangladesh Jute Research Institute (BJRI). Information on cropping patterns was collected from farmers at each of the sampling sites. The nutrient uptake data were calculated for these patterns on the basis of individual crops and their yields at the specific sites.

An assumed 35 percent fertilizer efficiency was used to convert the nutrients added during the growing period of the crop. This efficiency value was taken to be the mean value of all nutrients from the fertilizer obtained from the on-farm research data. The nutrient contents of sediments were determined for the total weight of sediments deposited at each site.

3.2 Radiocesium Sediment Accumulation Rates

Floodplain sedimentation rates were measured using the artificial radionuclide of cesium, ^{137}Cs. Sediment samples for Cs analysis were collected with sediment corers and by hand-sampling rectangular pits dug at the sampling sites. The September field study used a 15-cm-diameter PVC corer to collect samples. Cores were driven into the ground, dug out, and subsampled with the aid of a cm-scale extruder. Due to difficulties with sample sizes and obtaining volumes for bulk density analysis, the November field study collected samples with plexiglass tray cores (4 × 12 × 60 cm) driven laterally into pit walls. In addition, several cores >1 m long were taken with a portable vibracoring system using 10-cm PVC tubing.

Radiocesium is a fission byproduct produced in large quantities by the atmospheric testing of thermonuclear weapons, which began in the mid-1950s. These tests injected large quantities of ^{137}Cs into the stratosphere, where rapid mixing led to global fallout of the radionuclide beginning about 1956 for the northern hemisphere (Cambray et al. 1982; Figure 3.2). Cesium is a particle-reactive element that bonds strongly to sedimentary particles, making it a useful chrono-stratigraphic marker. The radionuclide has been used as a temporal control on sedimentation rates in a number of sedimentary environments, including river floodplains (e.g., Ritchey et al. 1975, and

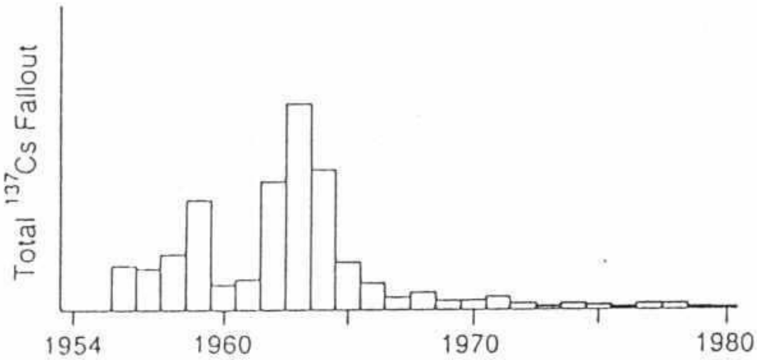


Figure 3.2 Radiocesium Fallout, 1954-1980

laboratory. The purpose of the outer permeable mat was to reduce the effects of surface erosion, raindrop splashing, etc., before and after flooding of the plots.

Sediment traps. Three sediment traps were set up in each of the 20 sample sites. The trap was designed to overcome problems previously experienced in trapping sediments on Bangladesh's floodplains (ISPAN 1993). These problems were: periodic flooding, floating vegetation, human interference, lateral wash from higher sites, raindrop splash, and bedload transport and resuspension during rapid flood flow. Each trap was initially filled with clean tubewell water. Because of 1994's low flood level, only 15 of the 60 traps were inundated by river water. These were collected on September 18 as the floodwater receded, tightly capped and sent to the laboratory for physical and chemical analysis of the contents.

3.1.5 Topsoil Sampling

Topsoil samples were collected from each sampling site between October 2 and 14, after floodwater recession. Each sample was a composite of 25 subsamples taken from the topsoil (0–10 cm) in the same field. Sampling was replicated three times in each field on subplots measuring 3.33 × 10 m. The number of samples collected totalled 78 (26 sample sites × 3 replicates). Samples were placed in heavy-duty polythene bags, sealed, and sent to the laboratory for chemical and physical analysis.

3.1.6 Site and Soil Descriptions

A detailed description made of each sampling site consisted of: physiographic characteristics of the area, a detailed history of agronomic practices, the depth and duration of seasonal inundation, farmers' information on the thickness of sediment deposited in average years and in the high 1988 flood, and a description of the soils. Detailed soil profile descriptions were made of the 12 main soil series occurring in the two blocks. Eighty-five soil samples collected from the main soil horizons of these soils were sent for physical and chemical analysis.

3.1.7 Water Samples

Water samples were collected from rivers and inundated fields in order to determine the amounts of suspended and dissolved nutrients they contained. The first batch of samples was collected on August 10 from the Jamuna and Dhaleswari rivers. Three samples were collected 30 cm below the surface. Three samples also were collected from each inundated sampling site between August 15 and 18. In all, 17 samples were collected and sent to the laboratory for analysis of dissolved nutrients.

Later, 29 water samples were collected from inundated fields between August 16 and 31. At weekly intervals between September 6 and October 4, 22 samples were taken at 30-cm depth from the Jamuna, Dhaleswari, and Jharkata rivers. These water samples were sent to the FAP 24 laboratory, which measured their suspended sediment contents.

3.1.8 Laboratory Analyses

The Bangladesh Institute for Nuclear Agriculture (BINA) laboratory performed the physical and chemical analyses of soil, sediment, and water samples using standard procedures (Hunter 1984). The laboratory analyzed soil and sediment samples for particle size, pH, organic matter, available nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, zinc, iron, copper, boron, manganese, and electrical conductivity. It should be noted that the particle-size limits used in soil analysis ($<2\mu$ clay, 2–20μ fine silt, 20–50μ coarse silt, $>50\mu$ sand) differ from those used by sedimentologists ($<63\mu$ silt+clay, $>63\mu$ sand) referred to later.

Soil and sediment pH was measured using a glass electrode in a 1:2.5 soil:water suspension. Electrical conductivity was measured using a conductivity bridge. NH_4 nitrogen was determined colorimetrically using a soil extract with NaOH, EDTA, sodium acetate, and bleach solution. Calcium and magnesium were determined using an atomic absorption spectrometer in a soil filtrate made in a lanthanum solution. Sulphur and boron were

Walling and Bradley 1989). Riverine sediments containing measurable quantities of ^{137}Cs as a significant fraction of the sediment load are derived from upstream surficial soils that have received fallout ^{137}Cs. Overbank flooding and the subsequent delivery of ^{137}Cs-laden sediment to downstream floodplain areas will provide enhanced levels of ^{137}Cs to the floodplain.

This study used two distinct approaches to provide sedimentation rates from ^{137}Cs profiles of floodplain sediments: penetration depths and isotope inventories. These approaches are described below.

A simple approach to modeling sediment accumulation rates from ^{137}Cs profiles is to examine the maximum depth of ^{137}Cs penetration in sediment cores (Figure 3.3). If diffusion of ^{137}Cs is negligible, and floodplain sediments are undisturbed, the penetration depth of ^{137}Cs will reflect the thickness of sediment deposited since the first significant input, in this case 1956–1994 (i.e., 38 years). Fallout cesium is strongly adsorbed by clay particles in surface horizons of the soil, although Cs has been found to be somewhat mobile under certain conditions (Frissel and Pennders 1983). Moreover, disturbance of floodplain surficial sediments is common in the study area and also cannot be

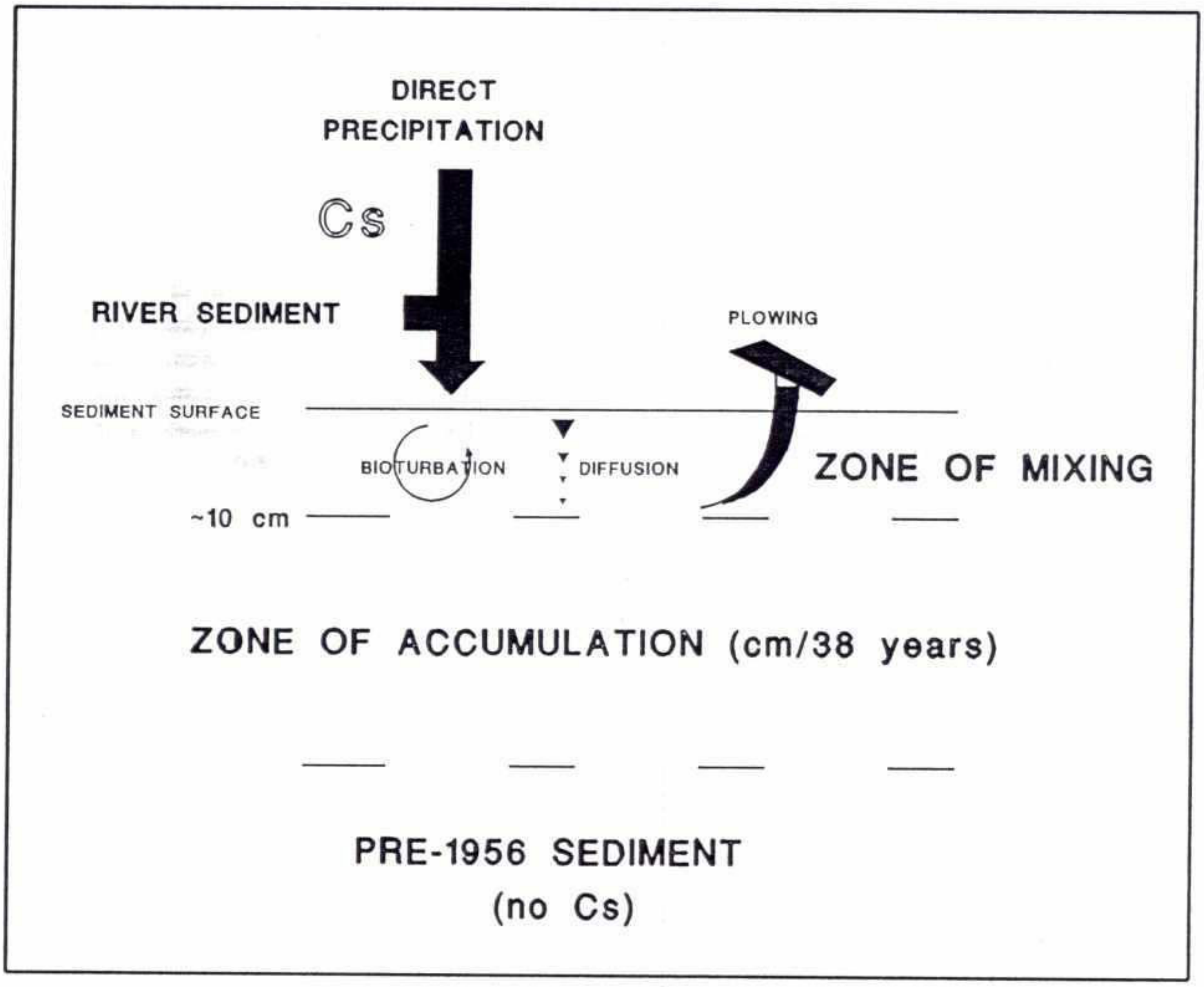


Figure 3.3 The Process of ^{137}Cs Accumulation in Sediments

ignored. However, if typical diffusion/disturbance depths can be established in a particular area, then first-order accumulation rates can be estimated by using the "excess" penetration depths for ^{137}Cs (i.e., beyond that expected by diffusion/disturbance). In this case, the excess penetration depth would reflect the thickness of sediment deposited since 1956.

This study attempted a second, indirect, approach that examined the total integrated ^{137}Cs activity per unit area (inventory) in floodplain sediments. In a floodplain area with net accumulation, the inventory reflects the sum of fallout ^{137}Cs and flood-borne sediments containing ^{137}Cs. Under steady-state conditions, therefore, the excess inventory (above atmospheric fallout) is proportional to the amount of sediment accumulated since 1956. Determining the transfer function from excess inventories to sediment accumulation rate requires estimating the average ^{137}Cs activity of flood sediments. Walling et al. (1992) developed a mathematical model that can be used to deconvolve ^{137}Cs activity profiles into atmospheric and sedimentation components, providing a way to determine average activities of flood sediments. The method assumes steady-state input of sediment and that grain-size variations in the study area are negligible.

Sediment grain size potentially is a major limitation of the inventory technique since much of the ^{137}Cs is bound to the fine fraction of the sediment. Variations in grain size, therefore, will strongly affect excess inventories. A secondary objective of this aspect of the study was to examine the control of textural variations on measured ^{137}Cs inventories, and to develop a procedure to correct ^{137}Cs inventories for these variations. The following section outlines the analytical methods this study applied to measure ^{137}Cs activities (and supporting analyses).

3.2.1 Radiocesium Activities

Gamma spectroscopy was used to measure ^{137}Cs activities. Samples were collected from sediment cores and pits; these were homogenized and packed into pre-weighed 70-ml plastic petri dishes that were labeled, weighed, and sealed with electrical tape. At the laboratory, the petri dishes were put on a low-energy intrinsic germanium detector (LEGe) coupled to a multichannel analyzer, where they were counted for 24 hours. After counting, the samples were dried in a 65°C oven for at least two days, cooled in a desiccator, and weighed using a top-loading balance. Radiocesium activities were determined using the integrated (net) area of the 661.66 keV photopeak. Net peak areas were multiplied by a detector-specific factor that accounts for detector efficiency using a particular counting geometry. Factors for each of the three detectors used were estimated by extrapolation from efficiency versus energy plots constructed using a liquid Harwell uraninite standard counted with the same geometry. Specific activities were calculated by dividing the total measured sample activity by the sample dry weight, and expressed as disintegrations per minute per gram of sample (dpm/g). The square root of the net counts was the standard error for the count data.

3.2.2 Textural Analyses

Samples for textural analysis were homogenized and a 15–30 gram aliquot was weighed. Aliquots were then disaggregated in a 0.05 percent sodium hexametaphosphate solution in combination with an ultrasonic bath. The sample was wet-sieved through a 63μ sieve to separate the sand and mud (silt+clay) fractions. To measure the total percentage sand fraction of the sample, the fraction remaining in the sieve was washed onto filter paper with deionized water, dried at 65°C, and weighed. The total weight of the silt and clay fractions was measured by putting the sediment-water solution that passed the wet-sieve into a 1-liter graduated cylinder and recording the volume. This was homogenized, and a 20-ml aliquot taken and placed in a 50-ml beaker. The beaker sample was dried at 65°C and weighed. The remaining graduated cylinder sample was concentrated by centrifugation at 7,000–9,000 rpm. Detailed granulometry of the silt ($>4\mu$) and clay ($<4\mu$) fractions was performed on the concentrated sample using a Sedigraph model 5100 x-ray digital settling analyzer.

3.3 GIS Mapping

A Geographic Information System (GIS) is a computerized system for the input, storage, analysis, and display of maps, aerial photography, satellite images, and other spatially referenced data. Essentially, any data with spatial coordinates can be analyzed and mapped using GIS. This study used a GIS to map and analyze natural resource and infrastructural conditions in the study area and study blocks. The digital database was used for baseline mapping, display and analysis of field data, and the construction of a GIS model of floodplain sedimentation processes. The GIS model produced a regional map of areas assumed to be receiving similar quantities of floodplain sediment deposition.

The GIS software packages used for this study were the vector-based pcARC/INFO GIS and the raster-based PC ERDAS GIS. Both are widely used in Bangladesh and internationally.

The data structure used to store digital maps in ARC/INFO is known as a *coverage*, which is an automated map containing sets of points, lines, or polygons that represent geographic features and associated attribute data. For example, a soil coverage would consist of digital polygons representing soil map units, each with a unique identifier linking it to a record in a database table containing descriptive attributes.

ERDAS, on the other hand, employs a *raster*, or grid-cell data structure, where each cell is represented by a display pixel, or picture element. Each pixel is assigned a data file value corresponding to a map attribute. For instance, numeric identifiers for soil types can be assigned to pixels that geographically coincide with soil map units.

3.3.1 GIS Database

The initial acquisition of data involved collecting and examining primary sources to assess the natural resource status of the study area and study blocks (Figure 3.4). Another purpose of this assessment was to stimulate development of an appropriate GIS model for determining sediment deposition regimes. The primary data themes acquired and used for this inventory were: hydrography (rivers), topography in the form of a digital elevation model (DEM), soils, geology, satellite imagery, roads, and embankments. The study collected detailed data for the study blocks and somewhat more generalized regional data. These data represent the agents of the floodplain sedimentation process in the GIS environment. From them FAP 19 derived additional data in the course of model development. These derived data included: distance from sediment source, inundation land type (flood depth regime), physiographic regions, historical changes in the Jamuna River left bank, and land cover during the 1987 flood. The source and quality of the primary and derived data themes are described below and summarized in Table 3.1.

The study also used the GIS to map the location of field reconnaissance areas, sediment trap locations, and sampling sites. Geographic coordinates for each location were collected in the field using a Global Positioning System (GPS) receiver that employs electronic signals from satellites specially designed for automated land survey and navigation. The field data points were then georeferenced to compile a field map for visual analysis and incorporation of the data into the GIS model.

3.3.2 GIS Data Themes

DEM. A digital elevation model (DEM) is a computerized representation of a continuous surface, usually that of the Earth. More specifically, it is an array of digitally stored numbers representing the elevations of discrete points on a surface. This virtual surface can be viewed by displaying the array of values on a computer monitor, where each point is represented by one pixel. Since the elevation values are geographically referenced, it is possible to apply mathematical algorithms to them for characterization and analysis of land surfaces.

FAP 19 has compiled a semi-detailed DEM (500 m × 500 m) based on spot elevation points from detailed Bangladesh Water Development

Table 3.1 Summary of GIS Data Themes

GIS Data Theme	Data Source	Source Scale/Resolution
DEM	BWDB maps, FINNMAP aerial photo maps	1:7920, 1:15840 BWDB maps 1:20000 FINNMAP maps 500 m resolution DEM
Hydrography	1989 SPOT maps	1:50000
Infrastructure	LGED thana maps	1:50000
Satellite Images	1987 Landsat MSS, 1993 Landsat TM, 1994 Landsat TM	MSS - 80 m resolution TM - 30 m resolution
Topographic Maps	Wilcox, Indian Atlas, SOB	Wilcox Indian Atlas - 1:63360 SOB - 1:50000
Urban Areas	AEZ maps, GPS data	1:250000
Soils	AEZ maps	1:250000
Proximity to Sediment Source	Sediment study hydrography (above)	80 m resolution
Flood Image Map	1987 Landsat MSS satellite image	80 m resolution
Physiographic Regions	Sediment study soils (above)	1:250000
Land Type Map	Sediment study soils (above), sediment study DEM (above)	1:250000, 500 m resolution
Jamuna Left Bank	1973 MSS image, 1994 TM image, various historical maps	MSS - 80 m resolution TM - 30 m resolution

Board (BWDB) topographic maps compiled during the early 1960s. This DEM can be used for the digital terrain analysis required for water resource, environmental, engineering, and urban and rural planning. GIS use in these applications typically requires DEM derivatives such as slope, aspect, contour, shaded relief, and 3-D perspective maps generated by digital terrain analysis. The principle use this study made of the digital elevation model (Figure 3.5) was in the preparation of a flood depth map for modelling sediment deposition regimes.

After the BWDB spot elevation points were digitized, a spatial interpolation algorithm was used for point-to-surface transformation, i.e., the point elevation data acquired during digitizing were transformed into a raster GIS file. These ERDAS GIS files have a 300 m pixel size and a 0.1 m elevation interval. However, it is important to note that the data resolution of the products depends on the data source, in this case, 500 m horizontal resolution and 0.1 ft. vertical resolution. A detailed account of this process is given in ISPAN 1995b.

For the mapping and analysis required in this study, FAP 19 extracted the portion of its DEM covering the study area. The data did not afford complete coverage of the area because they are 30 years old and because shifting of the Jamuna River channels left many voids. Furthermore, there also

Figure 3.4: Sediment Study Location Map

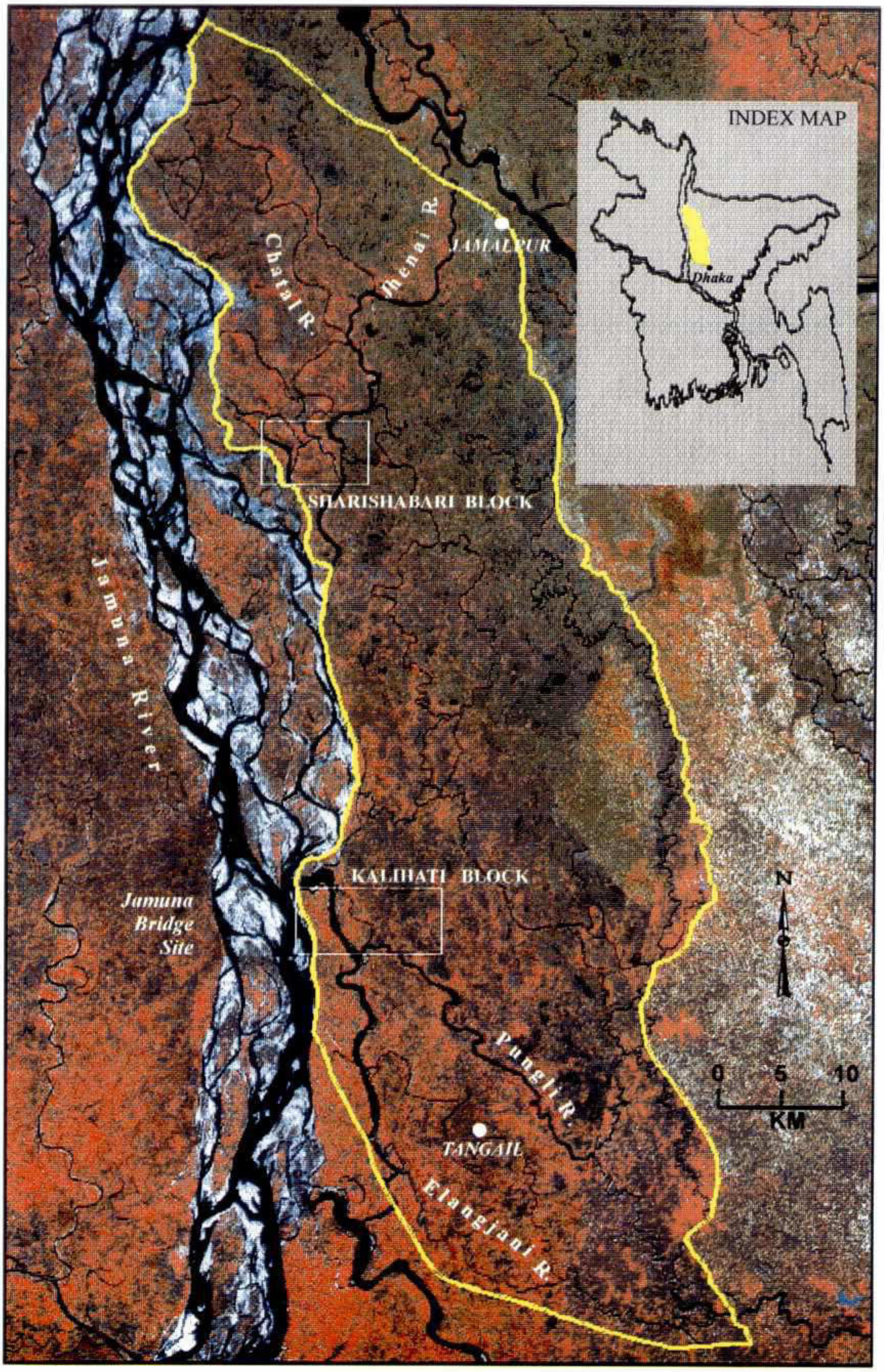


Figure 3.5: Digital Elevation Model of the Study Area

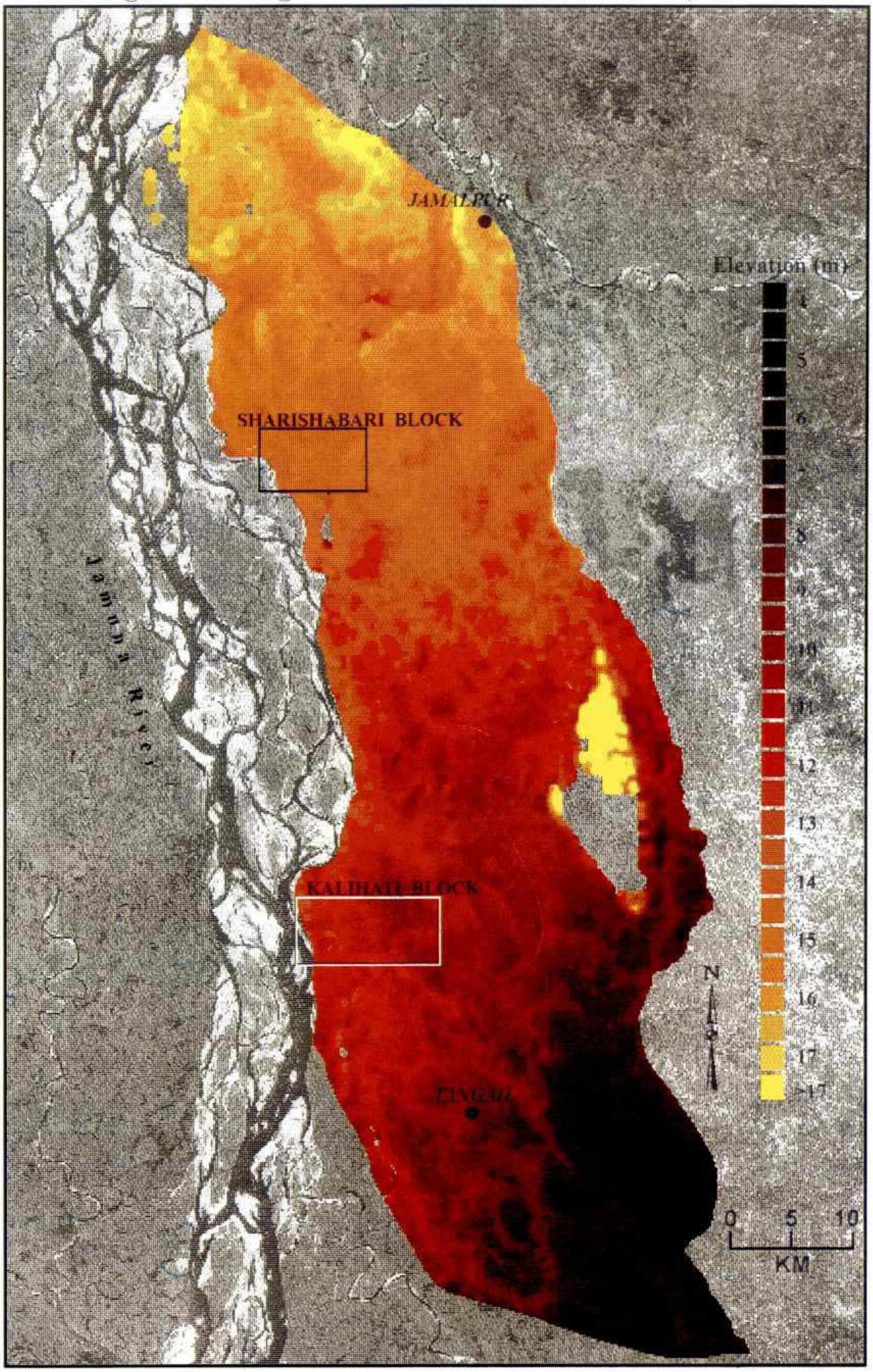


Figure 3.6: Hydrography of the Study Area

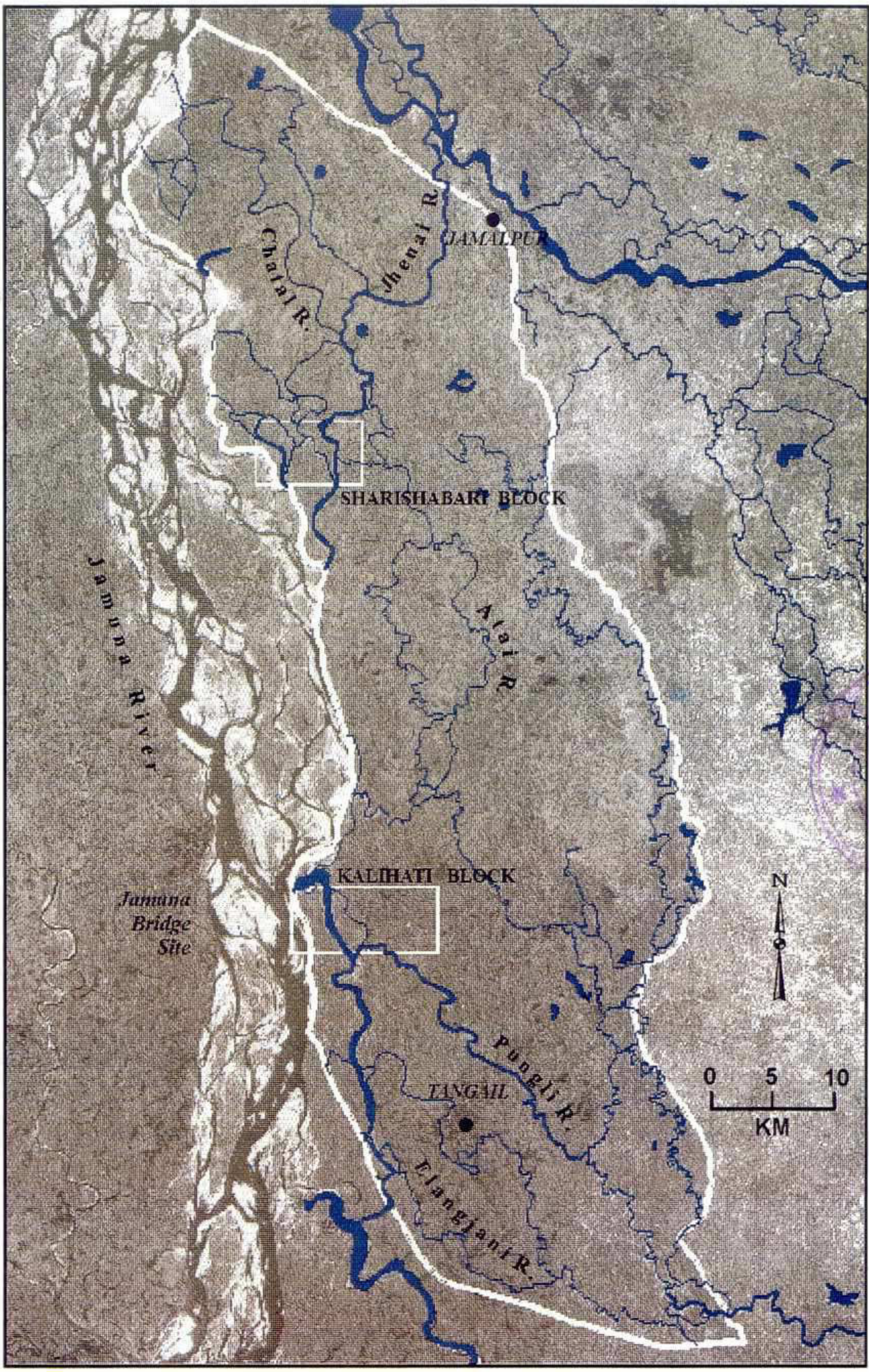
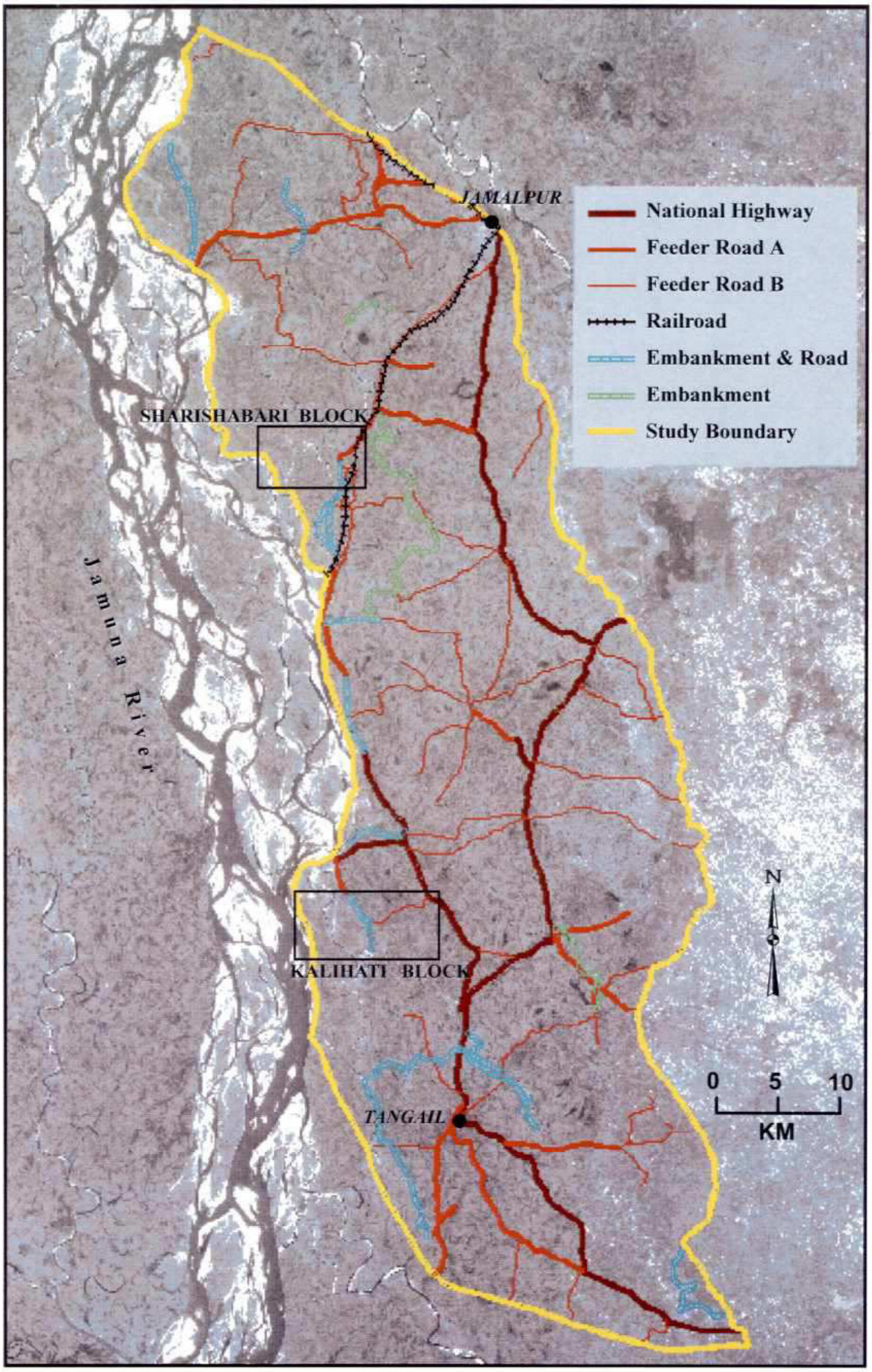
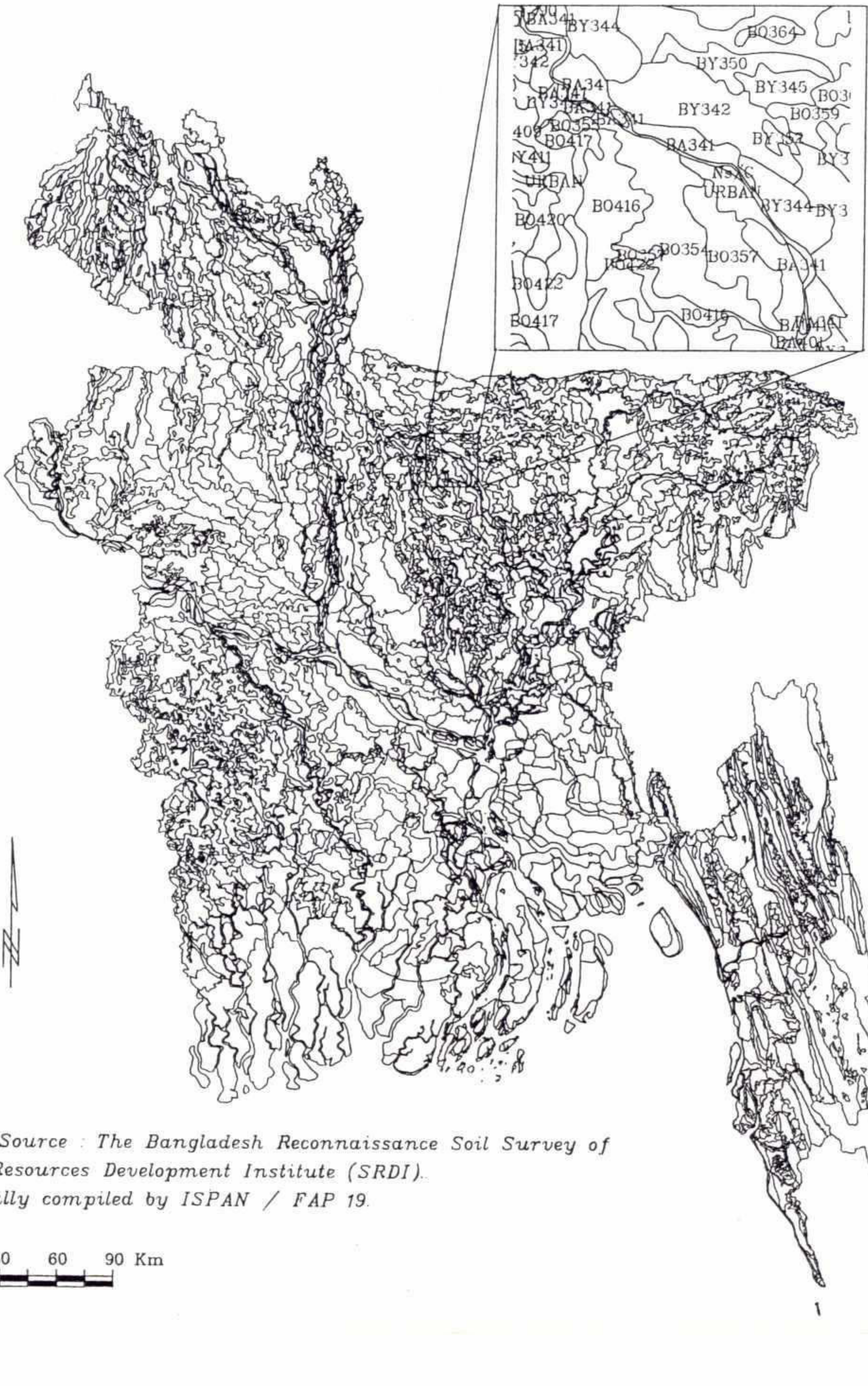


Figure 3.7: Infrastructure in the Study Area





Data Source : The Bangladesh Reconnaissance Soil Survey of Soil Resources Development Institute (SRDI). Digitally compiled by ISPAN / FAP 19.

Figure 3.9: Satellite Image of the 1987 Flood

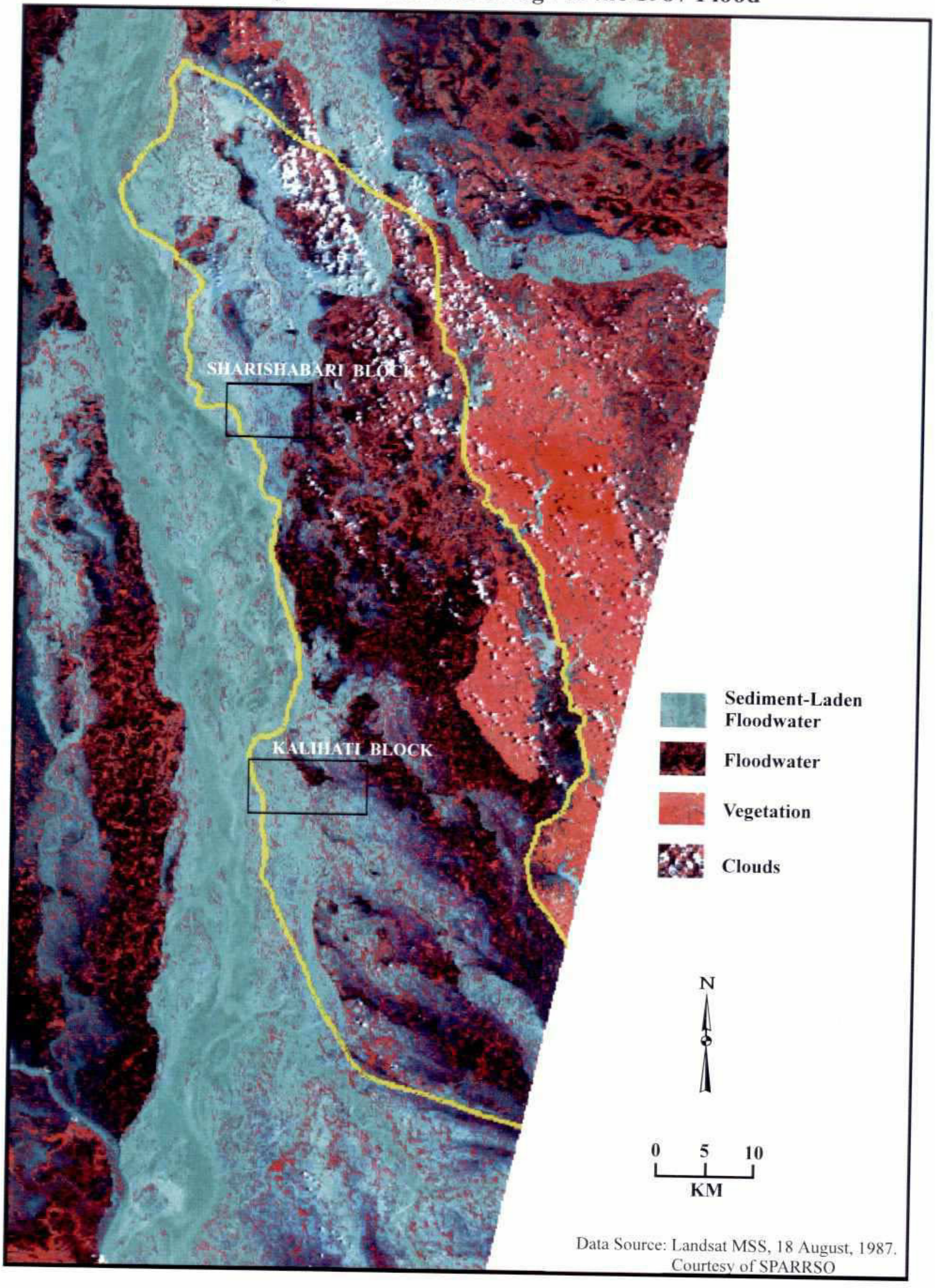


Figure 3.10: Physiographic Units of the Study Area

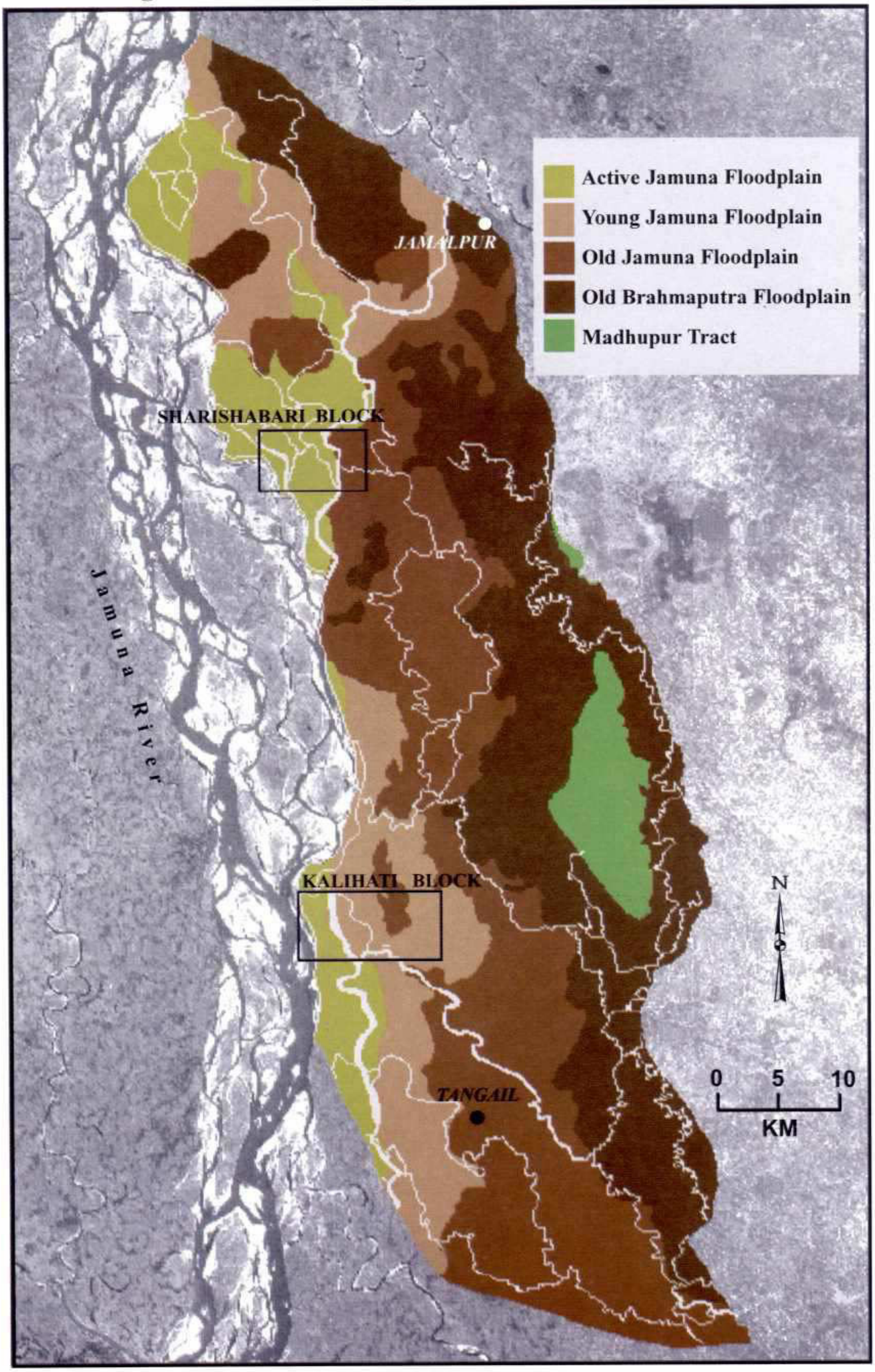


Figure 3.11: Inundation Land Types (Flood Depth) of the Study Area

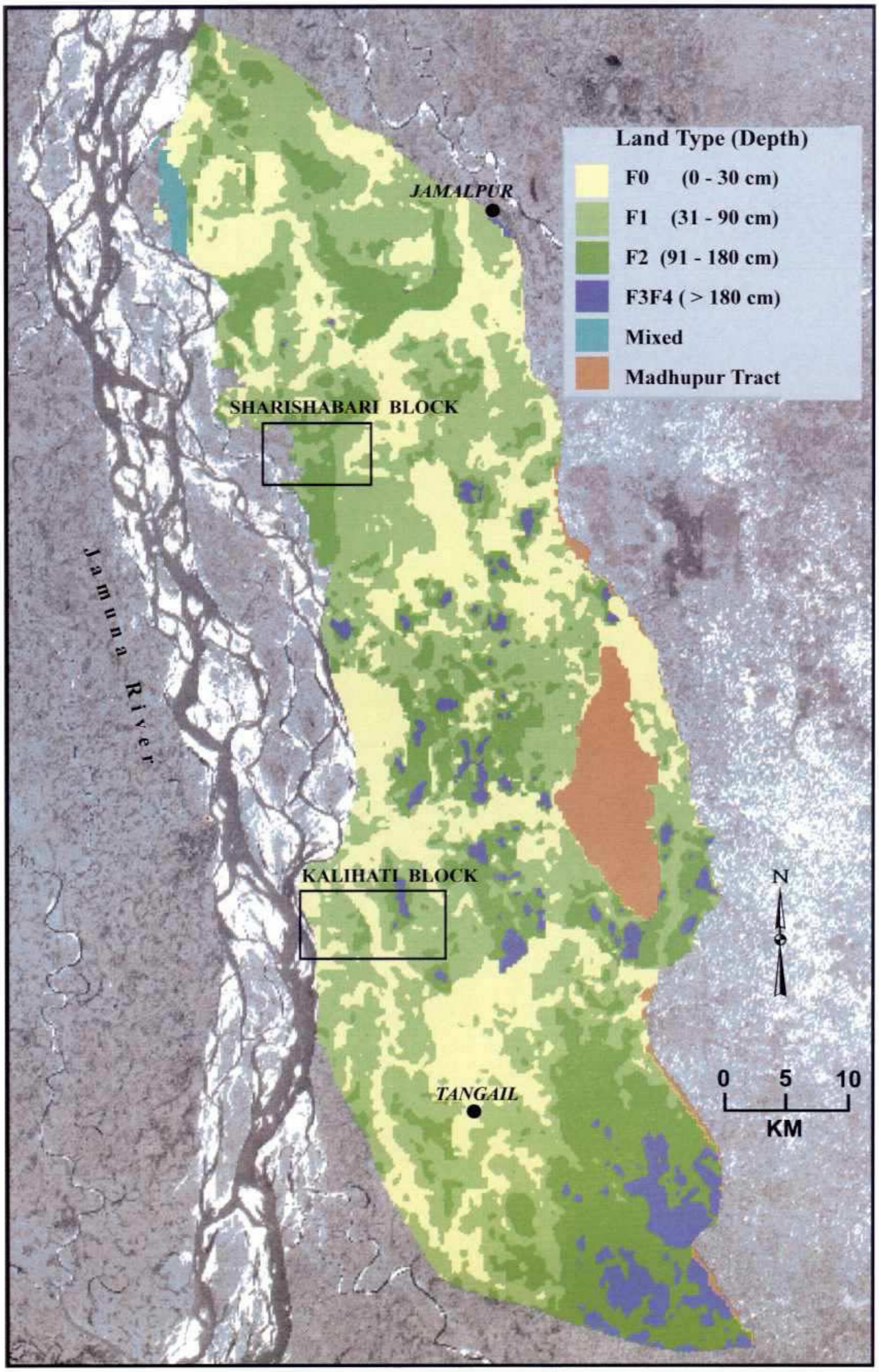
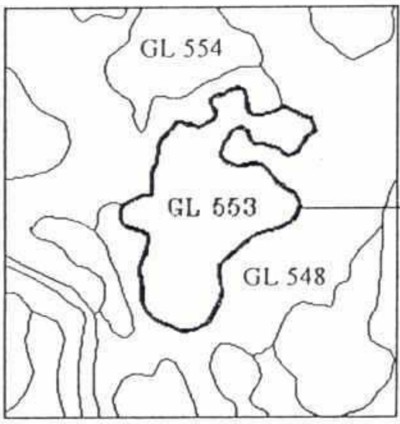


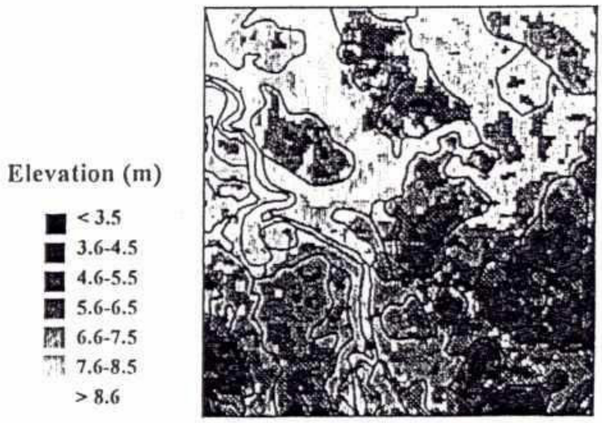
Figure 3.12: Procedure for Deriving Land Type Map

Polygon Attribute Table

AEZ Code (Soil Assoc.)	Land Type Distribution (%)				
	FO	F1	F2	F3	F4
GL 548	55	35	10	0	0
GL 553	31	44	20	5	0
GL 554	17	28	45	10	0

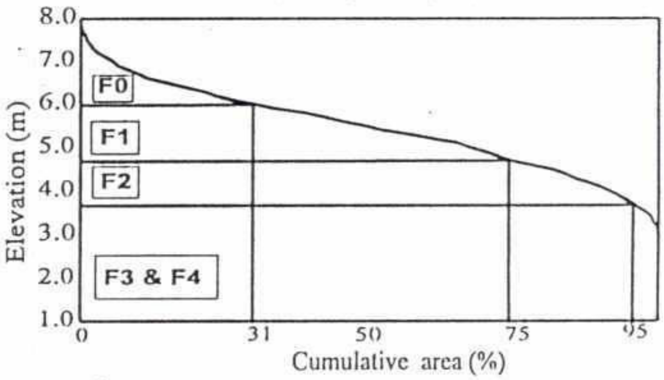


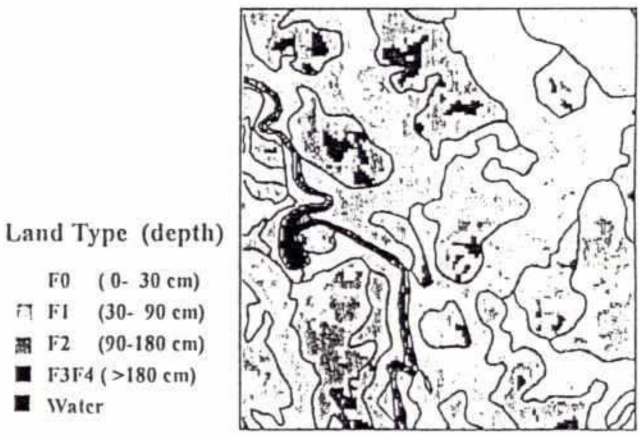
SOIL MAP



DEM

Area Elevation Curve





LAND TYPE

Algorithm for Delineating Land Type Map

1. Obtain the percentage of each land type (F_0 - F_4) in the soil association polygon from the ARC/INFO Polygon Attribute Table (PAT).
2. Locate the DEM pixels which geographically correspond to the same polygon via GIS overlay techniques.
3. Sort the DEM pixels by elevation in descending order.
4. Allocate the sorted pixels (high - low) to land type classes (F_0 - F_4) based on the percentages obtained in step 1, i.e., the highest pixels are allocated to highland areas (F_0) using the appropriate percentage, and so on down to lowland (F_4) which is allotted the lowest elevation pixels.
5. Repeat steps 1-4 until all soil association polygons on the map are classified.

Figure 3.13: Jamuna River Left Bank Alignment, 1830 to 1994

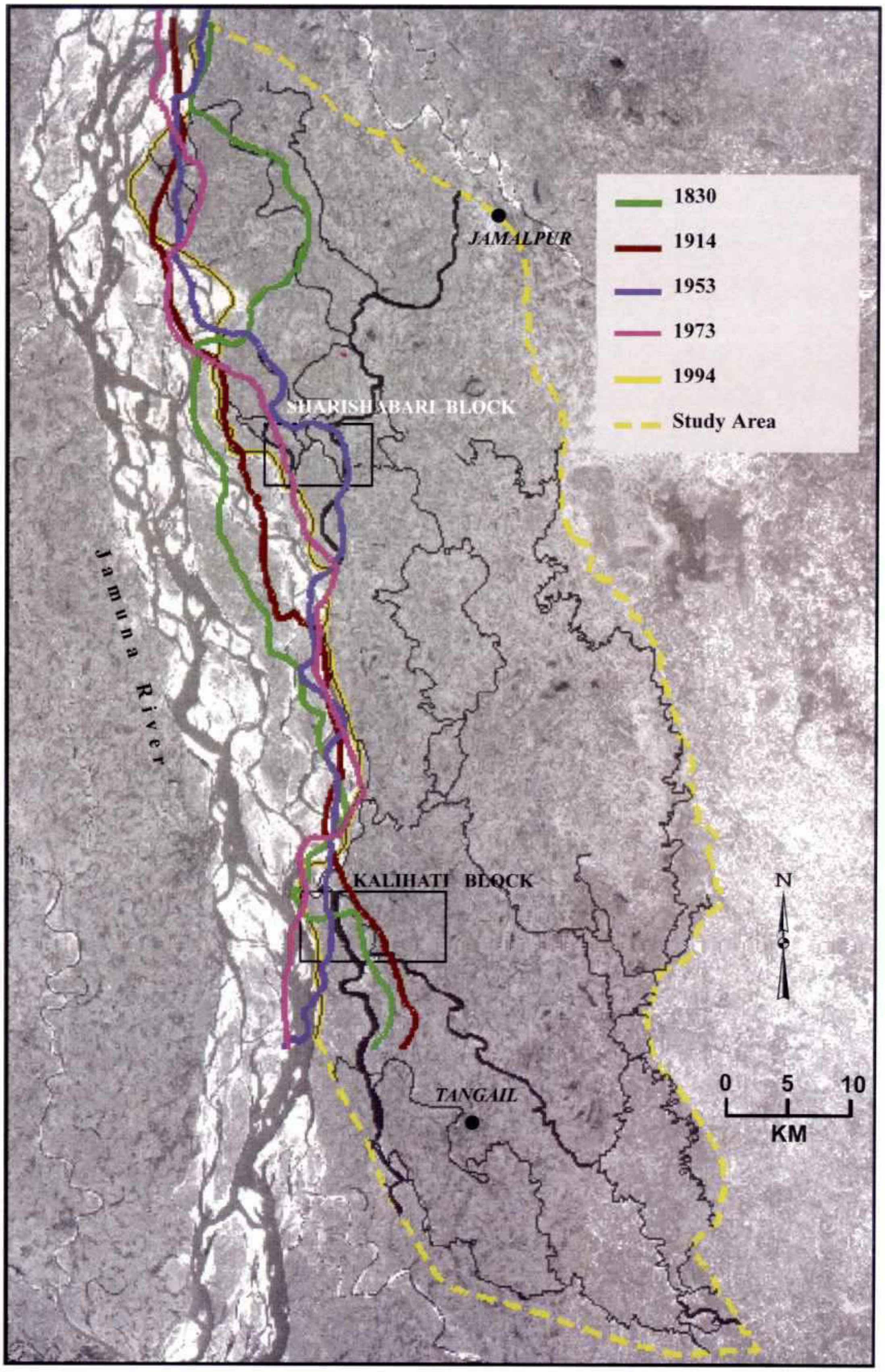
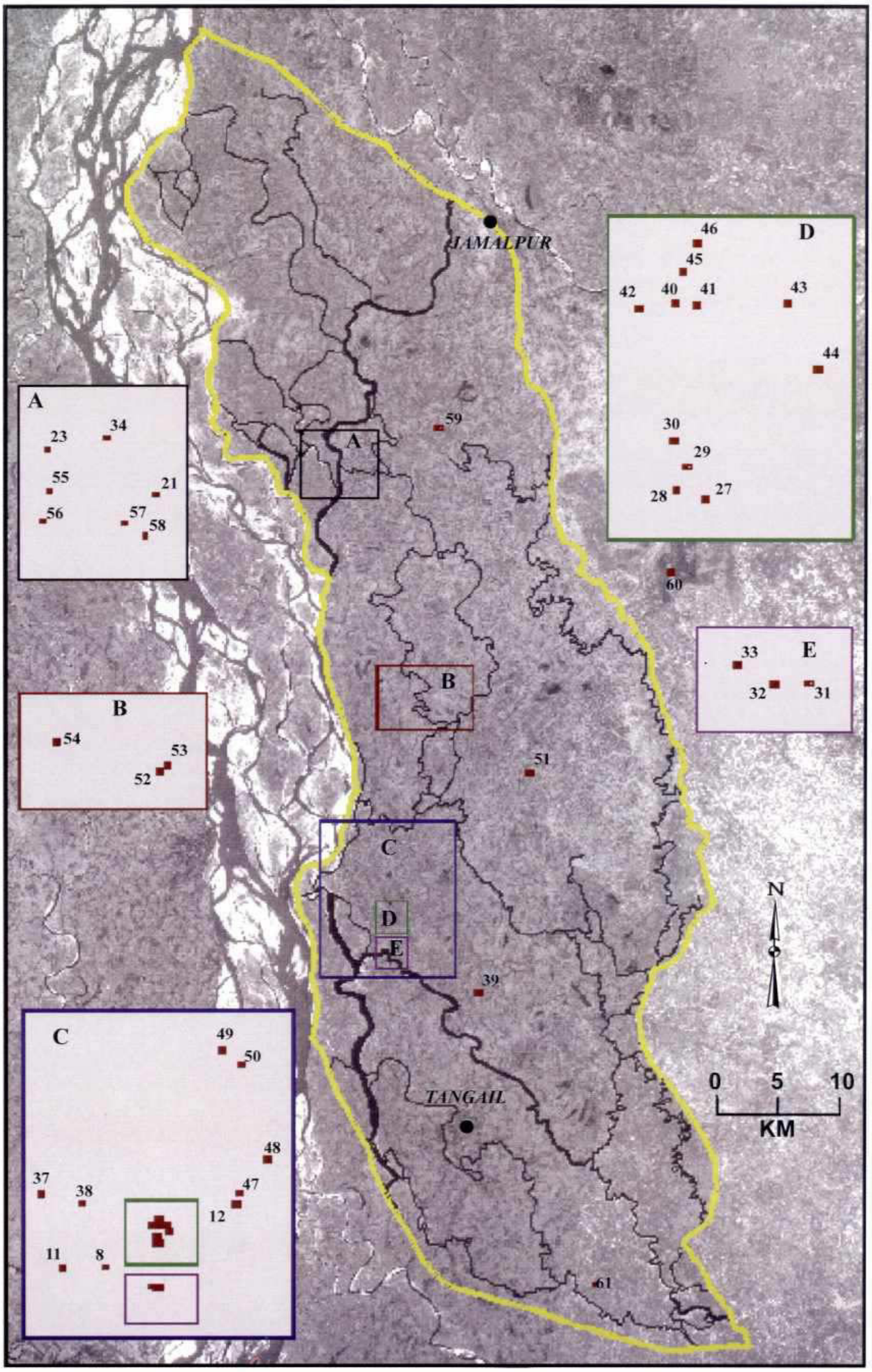


Figure 3.14: Location of Sampling Sites for Radiocesium Analysis



were numerous unsurveyed areas. Where available, more current elevation data from 1990 FINNMAP 1:20,000-scale orthophoto maps were appended to the data set. Estimates of elevation were also added to fill small voids in the study blocks.

Hydrography. FAP 19 developed a GIS-supported digital hydrography database for inclusion in its national database for Bangladesh. This semi-detailed data set, based on SPOT satellite image maps, includes all the major rivers, *khals*, large *beels*, and *chars* of Bangladesh. The intended users of this database are FAP component studies concerned with river morphology, hydrodynamic modeling, and the provision of data for regional and national natural resource applications and research.

The SPOT maps are based on multispectral satellite images of February 1989) with a ground resolution of 20 m and mapped at 1:50,000 scale. Survey of Bangladesh (SOB) topographic maps at 1:50,000 scale and BWDB topographic maps at 1:7,920 and 1:15,840 scales were used for reference and image interpretation.

The portion of the river database covering the study area was extracted for mapping and analysis (Figure 3.6). These data were appended to the 1994 Jamuna bankline digitized from a Landsat TM satellite image. Additional digitizing from the same satellite imagery added many smaller rivers and *khals* originally not included in the database. Details of rivers and *khals* for the Sharishabari study block were digitized from FINNMAP 1:20,000-scale aerial photographs acquired in 1990.

Infrastructure. This data layer includes roads, railways, and embankments in the study area (Figure 3.7). A regional map of national highways and feeder roads (types A and B) was digitized from Local Government Engineering Department (LGED) *thana* maps. The railway network included in this data theme was derived from the 17 agro-ecological zone (AEZ) maps (1:250,000 scale) published by UNDP-FAO under the Land Resources Appraisal of Bangladesh for Agricultural Development in Report 5 Volume (FAO 1988).

All raised roads and embankments in the Sharishabari study block were digitized from FINNMAP 1:20,000-scale aerial photographs acquired in 1990. These data can be linked to tabular information comprising dimensions and other physical characteristics.

Satellite images. Digital Landsat images from the 1973, 1993, and 1994 dry seasons, and a Landsat image of the August 1987 flood were used as a backdrop for thematic data and to aid in landscape interpretation. The 1993 data were appended to the 1994 image to give a single, complete coverage of the study area. The right bank of the Jamuna River was digitized from the 1994 image and from a 1973 image to determine the age of newly accreted land.

Soils. This study used a subset of the FAP 19 National Database (ISPAN 1995a) soils data that covered the study area (Figure 3.8). This soils data set was originally digitized from UNDP-FAO 1:250,000-scale AEZ maps (FAO 1988). AEZ soils data are primarily derived from the Reconnaissance Soil Survey conducted by the Soil Resource Development Institute (SRDI). Soils in this survey were mapped as members of a *soil association*, which is a group of distinct soils occurring contiguously in a regular pattern associated with the relief (AEZ Report 2). The AEZ Land Resources Appraisal also produced tabular data sets for use in land evaluation. The environmental attributes included in these data are those that directly affect crop production: soils, climate, and flood regime characteristics. FAP 19 acquired a digital soils map from the Agriculture Sector Team (AST) project, converted it into ARC/INFO format, and made refinements that included georeferencing and linking the AEZ data sets to soil map units. These data sets include information pertaining to landscape position, flood depth, physiographic attributes, etc.

Topographic maps. Several maps were used to digitize historical changes in the location of the Jamuna River bankline bordering the study area.

The maps used were compiled in 1830 (Wilcox), 1914 (Indian Atlas), and 1953 (Survey of East Pakistan). The banklines for all dates were then transformed to a common cartographic projection, the Bangladesh Transverse Mercator (BTM).

Urban areas. The geographic coordinates of important urban centers in the study area were extracted from the FAP 19 National Database (ISPAN 1995a). This information has been used to add landmarks to the study area maps.

Distance from sediment source. The study used a subset of the rivers data that included only the rivers within the study area. The vector features (lines and polygons) representing rivers were converted into ERDAS raster format with 80 m resolution pixels. Proximity analysis was then performed to encode each pixel in the image with its distance from the nearest river or *khal*. The pixel size of the file dictated the distance increment, which was 80 m.

Land cover during the 1987 flood. The August 1987 MSS flood image was classified using computer image processing to create a land cover map. A "clustering" routine was used for this purpose. This routine groups pixels with similar digital values and then assigns them to specific user-interpreted land covers or types. In this case, the image was classified into four categories: sediment-laden floodwater, floodwater (without sediment), vegetation, and clouds (Figure 3.9).

Physiographic regions. AEZ soil maps include an attribute indicating a physiographic region for each soil association polygon. In the study area, these regions are: the Active, Young, and Older Jamuna floodplain; Old Brahmaputra floodplain; and Madhupur Tract (Figure 3.10). These data represent past and present influences on landscape formation as interpreted by soil scientists. To create a physiographic map, soil association boundaries were "dissolved" to merge adjacent polygons belonging to the same physiographic region. In the GIS model, sediment deposition rates were assigned to each class in proportion to the likelihood that sediments would occur in floodwater.

Flood inundation land type (flood depth). A map of flood inundation land types was created from two of the primary data sources described above: the DEM, and digital soils data (Figure 3.11). The map is effectively a digital representation of "normal" flood depths during the monsoon season. The depth of flooding classes are equivalent to those used by MPO, as described in Section 2.2.6.

The soil unit in the AEZ maps is the *soil association,* which is a particular pattern of soil bodies made up of a number of *soil series* characterized by similar parent material and environmental conditions. These series are further subdivided into *soil phases* based on land use considerations. In Bangladesh, the most common soil phases are the depth-of-flooding inundation classes: highland, medium highland, lowland. SRDI made flood inundation interpretations for each soil phase during its Soil Reconnaissance Survey. Due to the complexities of soil associations, it is impossible to map the actual flood inundation boundaries at the reconnaissance mapping scale, i.e., the data describes the quantity but not the location of each flood depth class. The solution to producing inundation land type maps requires integrating the soils and topography data layers using GIS. Figure 3.12 contains a general description of the algorithm for this analysis and a process diagram for illustration.

The algorithm is performed sequentially on each soil association polygon in the input soil map to allocate its area to a flood depth category using the land type proportions in the ARC/INFO polygon attribute table together with the land elevations from the DEM. For instance, if 15 percent of a soil area belonged to the F0 class (highland), then the highest elevated 15 percent of the area in the polygon would be assigned to that class using the DEM. The remaining area in the polygon would subsequently be allocated to the flood depth classes lower in the landscape in the same manner. The elevation ranges needed to implement the allotment of DEM pixels to flood classes are obtained by constructing an area-elevation curve, i.e., a function for cumulative percentage of area versus pixel elevation (Figure 3.12). This curve facilitates the determination of the elevation "breakpoints" that define the flood class ranges. The land type algorithm was implemented with a suite of ERDAS programs and dBASE IV application programs.

Jamuna River bankline migration. Historical and image-derived maps of the Jamuna clearly show that the river has a dynamic channel. To document recent migration of the river's banklines, Landsat images from 1973 and 1994 were displayed on large-format, high-resolution computer monitors and the banklines were interpreted and digitized. Historical bankline positions were digitized from the best available copies of maps of the region compiled in 1830 (Wilcox), 1914 (Indian Atlas), and 1953 (Survey of East Pakistan). The banklines for all dates were then transformed to the BTM cartographic projection. Figure 3.13 shows the positions of the left bankline of the Jamuna for these dates. The banklines were overlaid using the ERDAS GIS to determine the relative ages of the land with respect to three categories: before 1953, 1953–1973, and 1973–1994.

3.4 GIS Modelling

The data themes described above were used to develop a GIS model for mapping regional sedimentation regimes. The primary data themes for the model were hydrography, land elevation (DEM), soil association, and a temporal series of satellite images, including the one of the 1987 flood. Interpretation of these data yielded thematic maps of distance from sediment source, estimates of flood depth, physiographic regions, spatial-temporal changes in the Jamuna River bankline, and extreme flood extent. The model development process also used field data on annual sedimentation rates as reported by farmers and derived from analysis of soil samples for ^{137}Cs radioisotopes. The sediment rates reported by farmers were used to represent minimum rates during average flood years. The model also used ^{137}Cs accumulation rate data to construct a function for predicting annual sedimentation rates based on distance from sediment source. The model yielded estimates of annual sedimentation rate and cumulative sediment deposition over 40 years (1954–1994) in a digital map format. The model was implemented with ERDAS. GISMO, a macro language that allows the overlay of images using mathematical and logical operators, was the primary ERDAS tool used for model implementation.

The model considers average annual sedimentation rates, sedimentation rates resulting from excessive flooding, flood depth during an average monsoon season, and land age (which is variable due to riverine erosion and accretion). Raster GIS maps were the model input for each of these spatial variables. The results are raster maps of the study area showing estimates of annual sedimentation rates and cumulative sediment deposition for the 1954–1994 period.

Annual sediment deposition rate. The formula FAP 19 used to estimate annual sedimentation rates is:

$$S_{annual} = (S_{distance} \times F_{87} \times F_{normal})$$

where

S_{annual} = annual sedimentation rate (cm/yr)

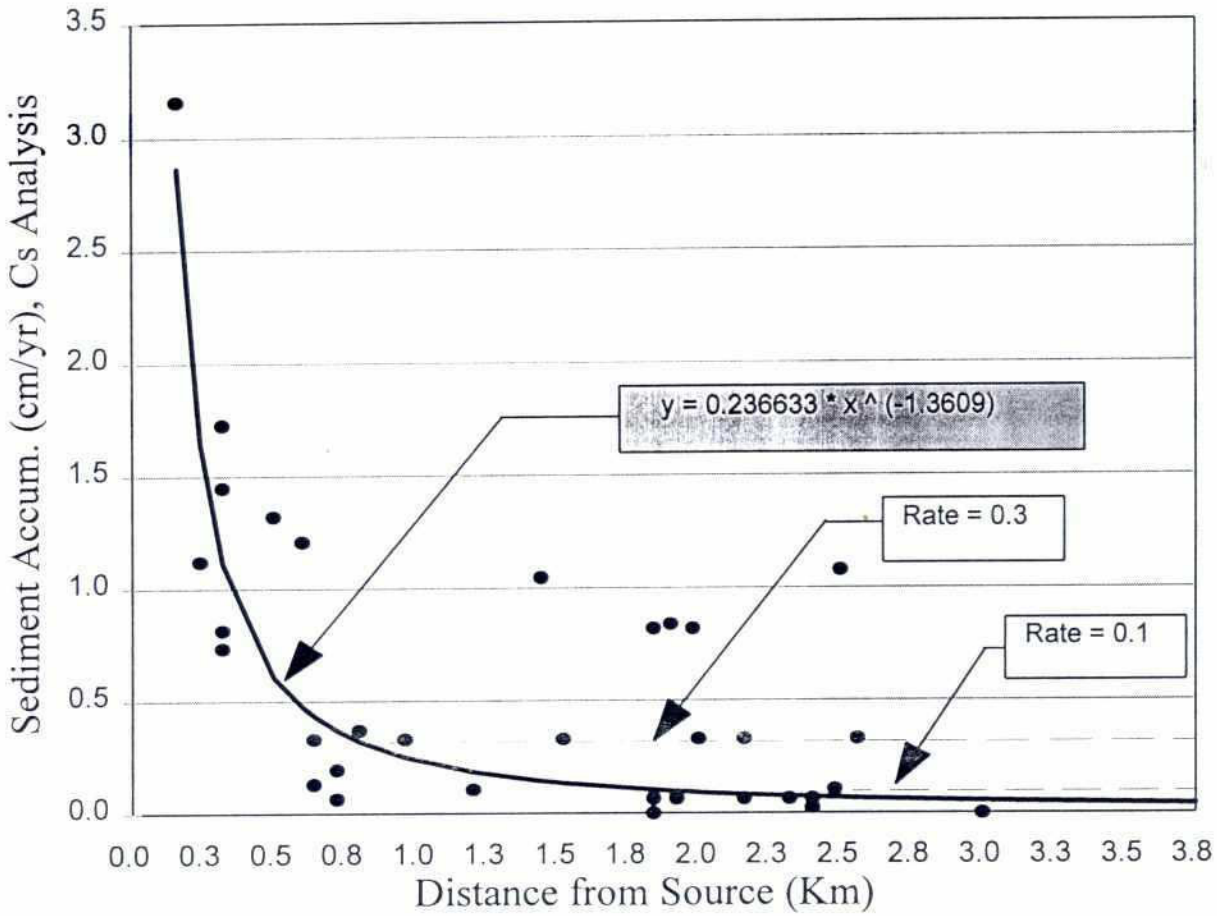
$S_{distance}$ = estimated sediment accumulation rate as a function of distance from sediment source (based on ^{137}Cs accumulation rate data)

F_{87} = an excessive-flood weighting factor based on a land cover map of the 1987 flood (0.5 for non-flooded areas, 1.0 for flooded areas)

F_{normal} = a flood-depth weighting factor based on a map of normal flood depths (0.5 for shallow flooding [F0], 1.0 for deep flooding [F1–F4]).

The cornerstone of the model is the $S_{distance}$ parameter, which is based on the relationship between ^{137}Cs sediment accumulation rates and their distance from sediment sources. The sediment deposition rates estimated from the ^{137}Cs analysis and a measurement of the distance of the sample points (Figure 3.14) from the nearest river or *khal* were used to develop a function describing this relation-

Figure 3.15 Function of Sediment Deposition with Distance from Source



ship. Since the geographic coordinates of the ^{137}Cs sample points had been obtained, the distance of the points from the nearest river or *khal* could be determined using GIS analysis. The points were overlaid on a raster "proximity" map, i.e., a map with pixels encoded with their distance from the nearest river. These distances, and the sediment deposition rates associated with the ^{137}Cs sample points, were used to develop the following distance-weighted function to predict deposition rates:

$$S_{distance} = D^{-1.3609} \times 0.236633$$

where

$S_{distance}$ = estimated sediment accumulation rate as a function of distance from sediment source

D = distance in km from the sediment source.

Figure 3.15 is a graph of this function. The deposition rate as predicted by the model is relatively high immediately adjacent to the source and approaches zero as distance from the river increases. Physiography-based minimum rates were imposed to level off the function, i.e., the distance function was used as the $S_{distance}$ parameter in the model until a lower threshold (minimum rate) was reached. The minimum rate is variable and linked to particular

Table 3.2 Sample Model Calculation

Model Parameter	Map	Map Attribute	Value/Factor
$S_{distance}$	Distance function or physiographic map	2 mm/yr from function or 3 mm/yr minimum for Young Jamuna floodplain	3 mm/yr
F_{87}	1987 flood map	Sediment-laden floodwater	1.0
F	Flood depth map	F0	0.5
A	Land age map	Accreted 1953–1973	30 years

CALCULATION:

$S_{annual} = S_{distance} \times F_{87} \times F = 3\text{ mm} \times 1.0 \times 0.5 = 1.5\text{ mm/yr}$

$S_{40} = S_{annual} \times A = 1.5\text{ mm/yr} \times 30\text{ years} = 45\text{ mm of sediment for the period}$

physiographic units (see Figure 3.10) and is based on field observations and results of the ^{137}Cs analysis. The more dynamic physiographic units, the Active and Young Jamuna River floodplains, were assigned a minimum rate of 3 mm/yr. Less active units, the Older Jamuna and Old Brahmaputra floodplains, were assumed to have a minimum rate of 1 mm/yr. The points on the function where it is leveled off are indicated by horizontal dashed lines in Figure 3.15.

The second model parameter, F_{87}, is a weighting factor that modifies $S_{distance}$ based on a map of the 1987 flood. The categories of a land cover map based on the 1987 flood satellite image (see Figure 3.9) were used to assign a weight to the F_{87} factor: a value of 1.0 for the sediment-laden floodwater category and 0.5 for all other categories (other floodwater, vegetation, and clouds).

The third parameter in the model, F_{normal}, is also a weighting factor. In this case the factor tempers $S_{distance}$ on the basis of "normal" flood depths as indicated by the inundation flood depth map (see Figure 3.11). The F_{normal} factor was given a value of 0.5 for F0, the highland areas that normally receive flood depths of only 0–30 cm, and 1.0 for all other inundation flood depth classes.

Forty-year cumulative sediment deposition. The cumulative sediment deposition for 40 years (1954–1994) was also estimated by the GIS model. This time span coincides with that of the ^{137}Cs analysis of soil samples for determination of sediment accumulation rates. The formula for this component of the GIS model is:

$$S_{40} = S_{annual} \times A$$

where

S_{40} = cumulative deposition (cm) from 1954 to 1994
S_{annual} = annual sedimentation rate as estimated by the GIS model (cm/yr)
A = age of the land.

This step in the model is fairly straightforward in that the output of the GIS model for the S_{annual} equation is multiplied by land age as determined using the map of changes in the position of the Jamuna River left bank (see Figure 3.13). The relative ages of land in the study area were determined using the map, which uses three classes, before 1953, 1953–1973, and 1973–1994. These relative age categories are roughly equivalent to land ages of ≥40, 30, and 10 years, respectively.

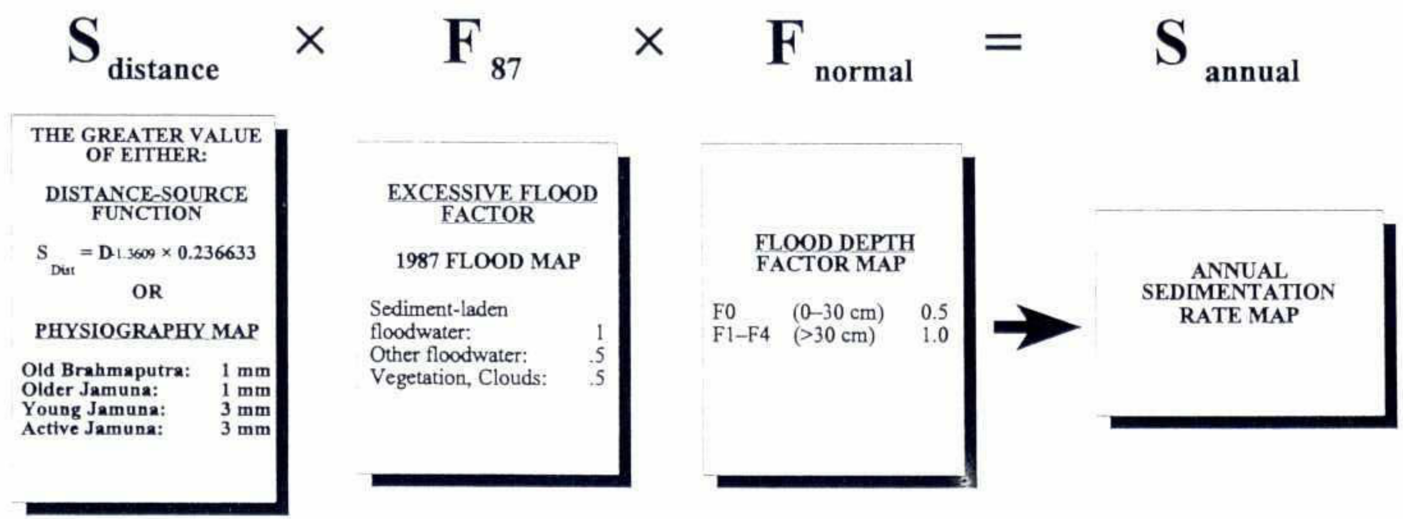


Figure 3.16 GIS Model for Annual Sedimentation Rate

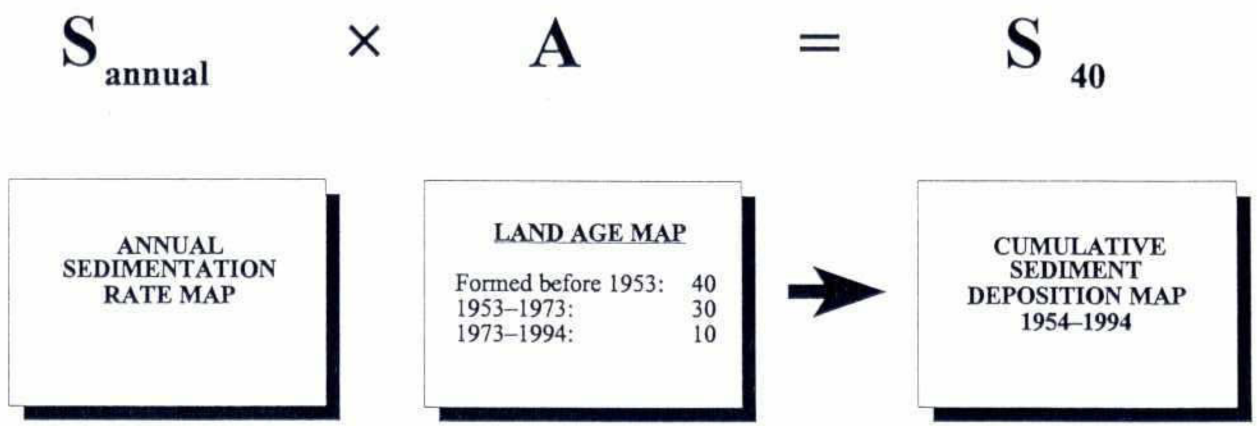


Figure 3.17 GIS Model for Cumulative Sediment Deposition (1954–1994)

GIS implementation. GIS "map algebra", using maps as variables, was employed to implement the model. The map variables were mathematically overlaid pixel by pixel, i.e., geographically coincident pixel values from each map were the basis for calculating numeric output to be assigned to pixels in an output GIS map. Figure 3.16 illustrates how the model was executed. Below each parameter of the equation in the figure are boxes indicating the corresponding map(s) with which each was represented. The values assigned to each map attribute for model calculations are listed below the map names. A logical expression is implemented in the case of the $S_{distance}$ variable where the distance function value is used only if it is greater than the minimum rate thresholds for each physiographic unit. The output from this first equation of the GIS model (S_{annual}) is subsequently used as input to the second equation for determining cumulative sediment deposition, as illustrated in Figure 3.17.

A sample calculation for a single geographic location (coincident pixels) on the image maps will help clarify the model implementation (Table 3.2). The map attributes indicated correspond to the values/ factors in the table as specified by the model. The calculations yield a 0.15 cm/yr annual sedimentation rate and a 4.5 cm cumulative sediment deposition.

Figure 4.6 shows the model output for S_{annual} for the entire study area. Annual sedimentation rates in this map range from 0 to 74 mm/yr. Cumulative deposition (S_{40}) for the period ranges from 0 to 296 cm.

Model rationale. The distance function used in the GIS model appears to offer a plausible representation of the sedimentation process close to sediment sources. The deposition rate predicted by the model is relatively high immediately adjacent to the source, then drops off rapidly to roughly 1 mm/yr at 2 km. Realistically, this asymptotic function cannot be considered a valid model at any distance. In the real-world situation, the rate would level off at some base level until forced to zero by a rise in topographic elevation. This is why physiography-based minimum rates were imposed to level off the function. The use of physiography makes sense here since all the units within the study area are floodplains categorized according to relative depositional activity. The dynamic physiographic units, the Active and Young Jamuna floodplains, were assigned a minimum rate of 3 mm/yr. This threshold is based on the mean of six ^{137}Cs sample rates for these physiographic units, which were clustered at the low end of the data range. The more stable Older Jamuna and Old Brahmaputra floodplains were assigned a minimum rate of 1 mm/yr. This threshold is supported by both the mean of all the ^{137}Cs sample rates for these physiographic units and by rates reported by farmers (see Tables 5.1 and 5.2).

The F_{87} model parameter is based on a satellite image of the unusually severe flood of 1987. The map represents empirical geographic data on areas inundated by sediment-laden floodwater or by non-riparian floodwater, and areas that were not flooded. The image classification is supported by the physiographic unit map (Figure 3.10), which shows a strong correlation between the Active and Young Jamuna floodplains and sediment-laden water in the flood image (Figure 3.9). Thus, using the satellite image and GIS analysis, a detailed map showing flooded areas and the generalized physiographic units was created to a resolution of 80 m (image pixel size).

The flood-depth factor (F) used in the analysis is based on the best map of flood depths and the best digital topographic data available in Bangladesh, which were combined using GIS analytical techniques.

Cumulative sediment deposition was determined for the 1954–1994 period since this is the time span covered by the ^{137}Cs soil sample analysis. Land age (A) was considered in the model to account for the effects of riverine erosion and accretion in the active floodplains adjacent to the Jamuna River (Figure 3.13). In other words, some land has accreted since 1954 and is therefore less than 40 years old. Only a small portion of the study area, approximately 5.4 percent, fell into this category. Nevertheless, the land age information helped calibrate the cumulative deposition rates to actual field conditions.

3.5 Literature Surveys

The ISPAN library and other archives in Bangladesh were searched for information on flooding, sedimentation, and associated effects on soil fertility. This included a search of MPO, BARC, SWMC, BWDB, FAP, and regional studies in peer-reviewed literature. An additional review was conducted in the United States of international literature (technical and peer-reviewed) relating to floodplain sedimentation processes, soil fertility in floodplains, research methodologies, and prior modelling efforts. The searches paid particular attention to locating results from other Asian rivers (e.g., Mekong, Indus, Yellow, etc.). Appendix III contains a bibliography of the results of the local and international searches to aid future researchers. Chapters 1, 2, 5, and 6 of this report present information gleaned from these studies.

Chapter 4

DATA AND RESULTS

4.1 Sediment, Soil, and Water Analysis

Maps of the Sharishabari and Kalihati study blocks, shown with sample site locations and infrastructure in Figures 4.1a and b, were developed for use in the presentation and interpretation of field data. Land type mapping of the study blocks was done to gain an understanding of flooding in normal years. Figure 4.2 shows the distribution of these depth-of-flooding land types in the two study blocks as surveyed for this study in 1994. The relative proportion of land in each land type category is shown in Table 4.1.

The quantity of sediment deposited in the study area in a normal flood year could not be measured directly because of the very low flood level in 1994. Only a few areas along the rivers and on nearby low-lying land were inundated by river water and received sediment deposits. However, local farmers at each sampling site provided information about the thickness of sediment deposited in 1994, in average flood years, and in the high flood of 1988. This reported information is shown in Figures 4.3a and b.

Table IV.1a and b in Appendix IV contains data on the physical characteristics of sampling sites in the Sharishabari and Kalihati blocks. The following sections detail the quantity and nutrient contents of sediment samples, and Chapter 5 interprets these data.

4.1.1 Sediment Quantity

Farmers' information. Tables 4.2a and b present the information farmers provided on the thickness of sediment deposited at each sampling site in an average year and in 1988. For comparison, the tables also list the thicknesses measured at the sampling sites.

Sediment traps. Five sampling sites with sediment traps were inundated for 5–35 days and received river water sediment. These sites, 2, 3, 7, 8, and 10, were on the Active and Young Jamuna floodplains. Table 4.3 shows the weight of the sediment deposited at each of these sampling sites. The results are expressed as the mean value of three replicated samples. Sites 10 and 2 were topographically lower than the other sites. Only two sites

Table 4.1 Land Type Distribution in Sharishabari and Kalihati Blocks

	Percent Distribution of Land Types			
Study Block	Highland	Medium Highland	Medium Lowland	Lowland
Sharishabari	0	51	42	7
Kalihati	13	58	23	6

Figure 4.1a: Sharishabari Block and Sample Sites

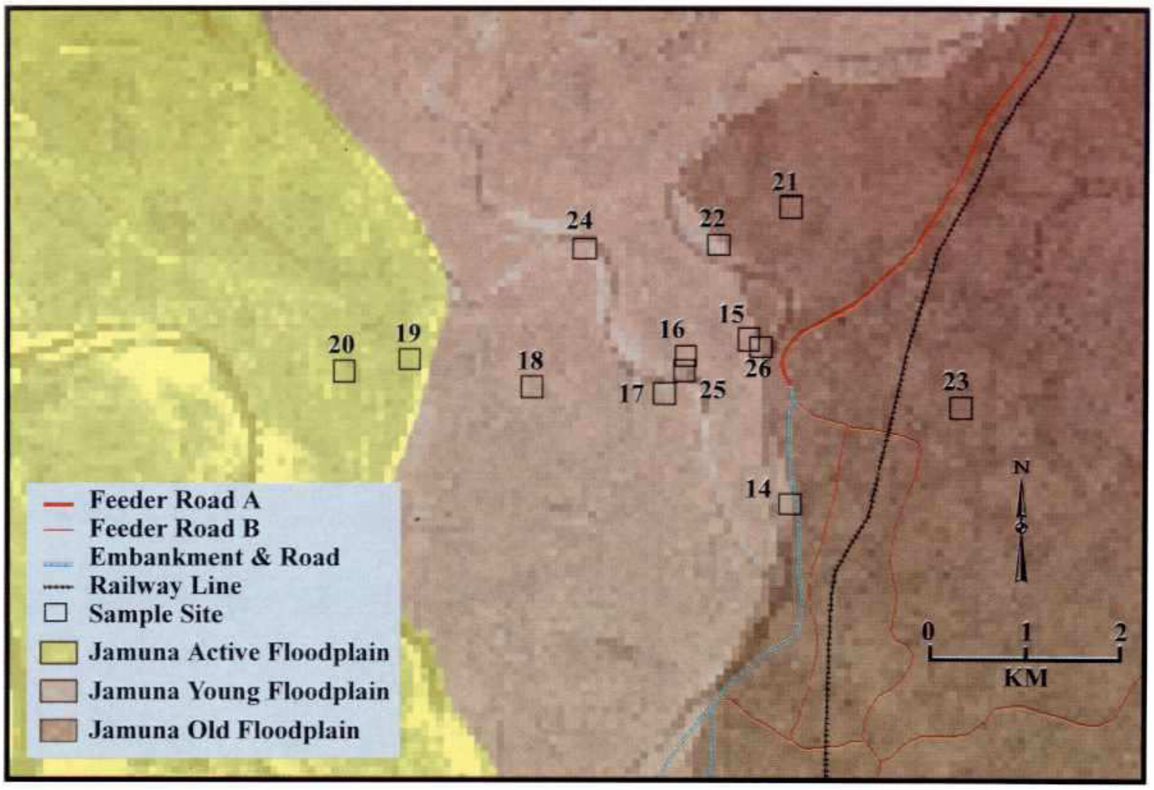
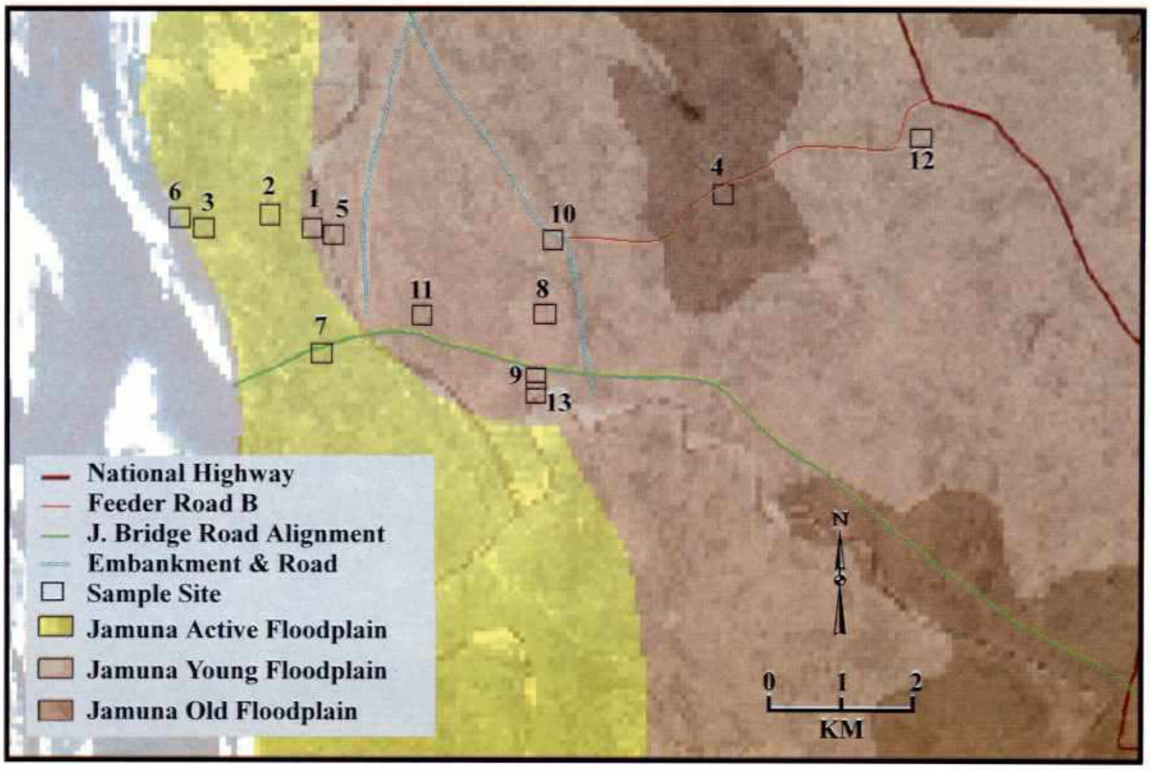
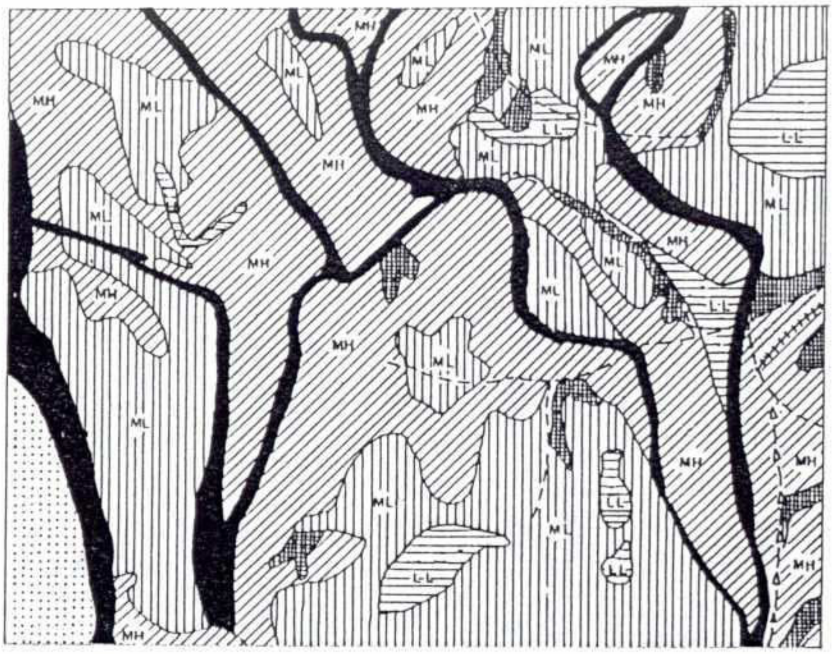
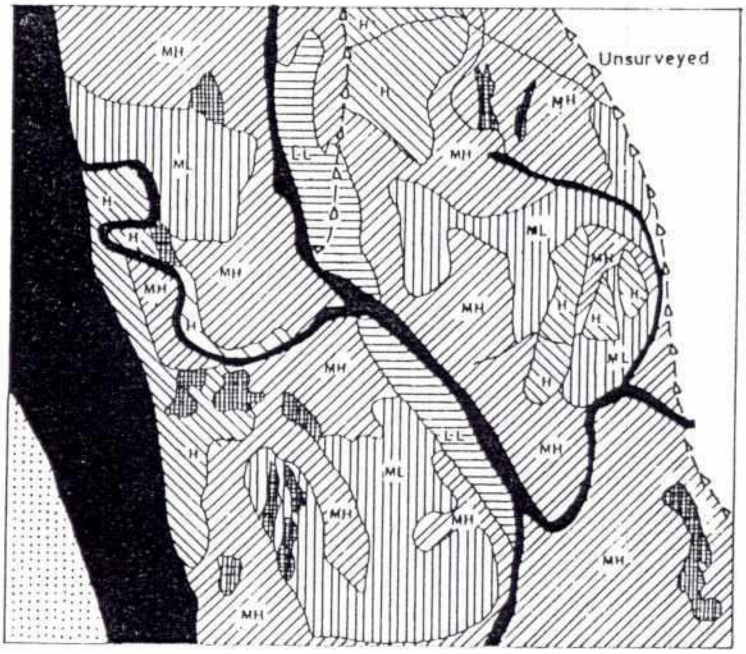


Figure 4.1b: Kalihati Block and Sample Sites





Sharishabari Block



Kalihati Block

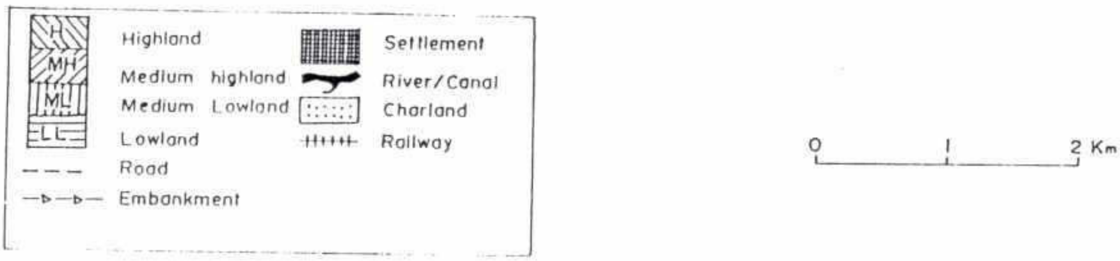


Figure 4.2 **Land Type Distribution Maps of the Sharishabari and Kalihati Blocks**

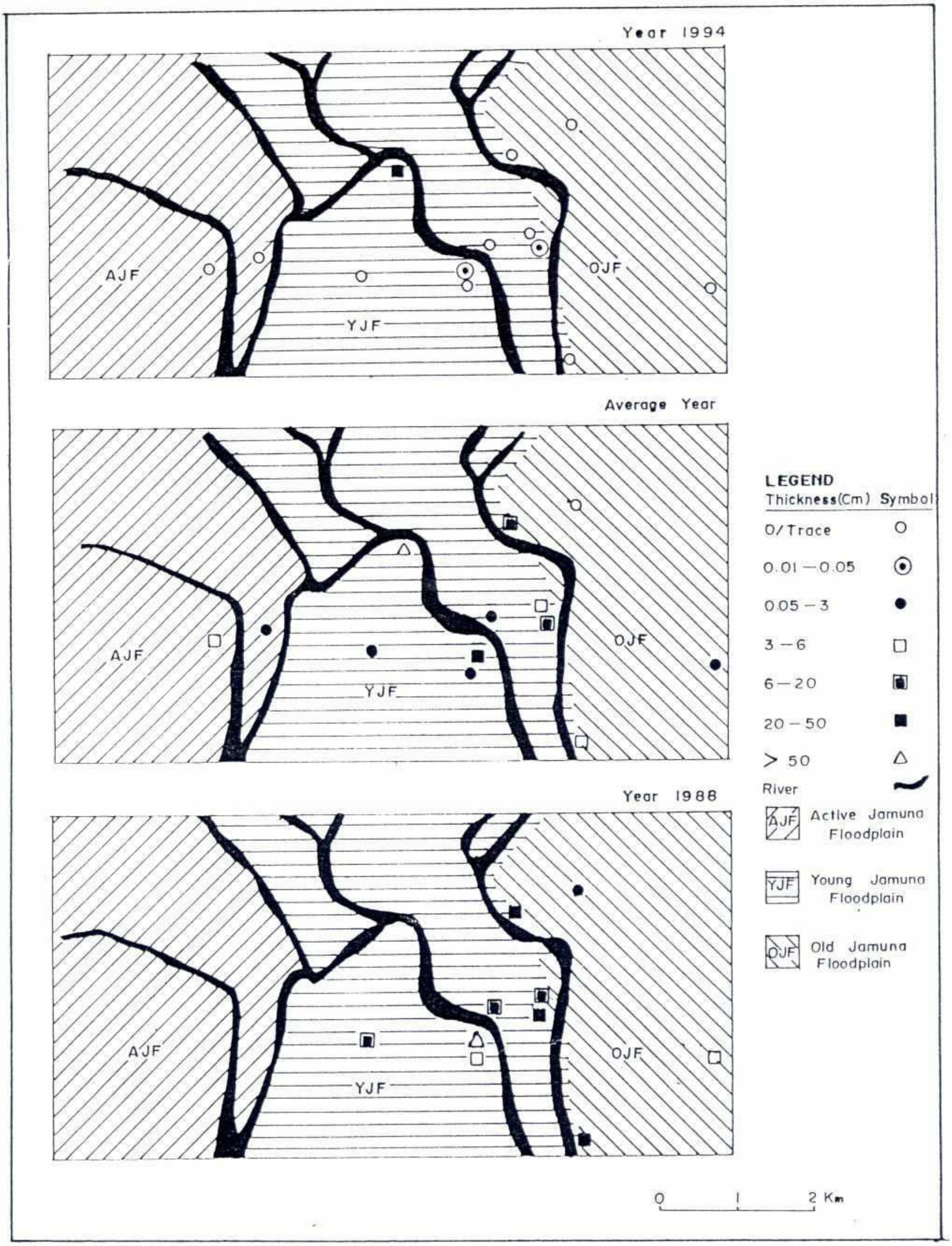


Figure 4.3a Farmer Reports of Sediment Deposition in Sharishabari Block

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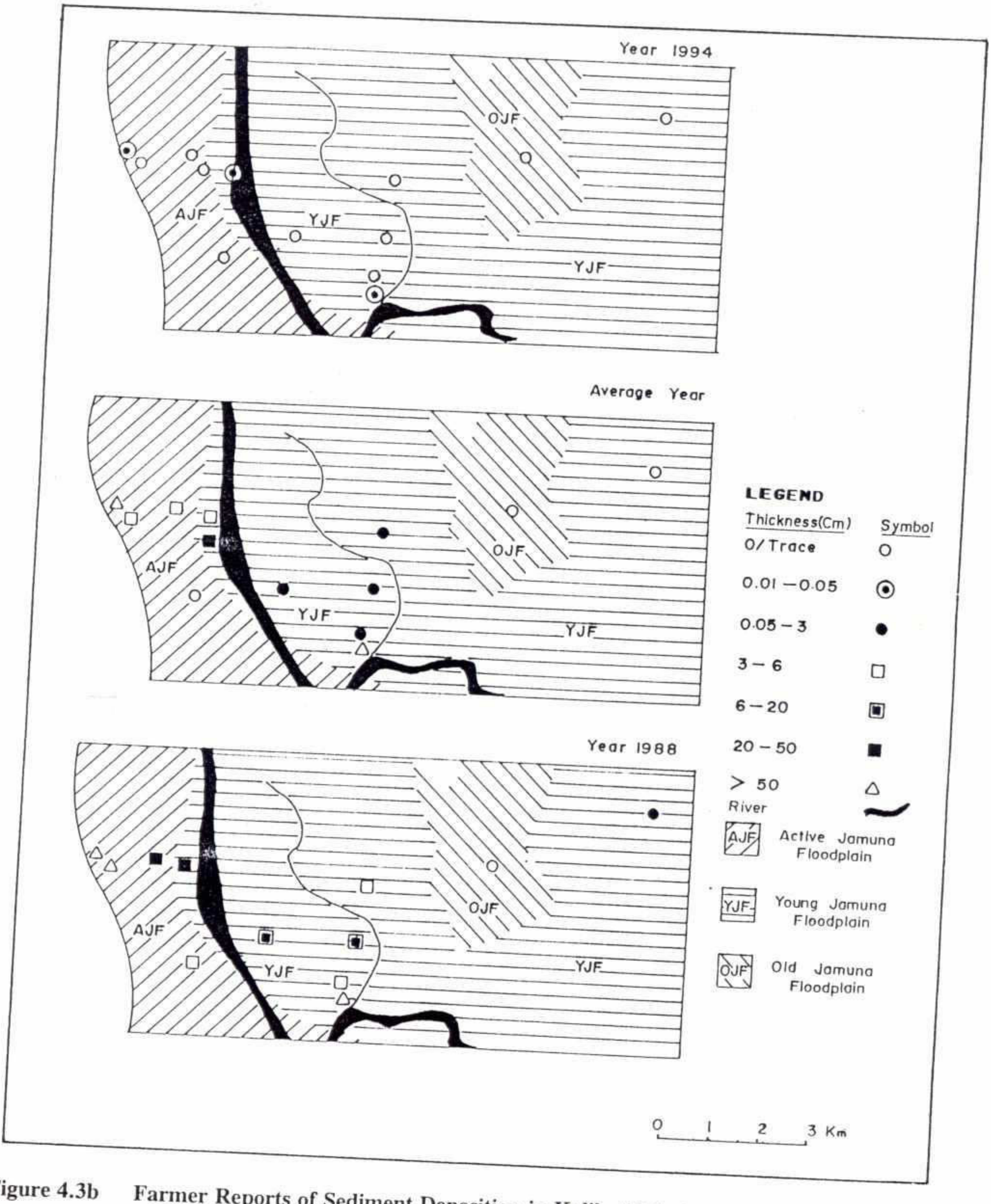


Figure 4.3b Farmer Reports of Sediment Deposition in Kalihati Block

Table 4.2a Flooding and Sediment Deposition, Sharishabari

Site No.	Physiographic Unit	Flood Depth and Duration: Normal Year Depth (cm)	Normal Year Duration (days)	1994 Depth (cm)	1994 Duration (days)	Sediment Deposition: Normal (cm)*	1988 (cm)*	1994 (cm)†
14	AJF	70–90	120	0	0	4–5	30	0
15	YJF	180–210	130	26	3	5	10–12	0
16	YJF	60–90	120	0	0	1	15–20	0
17	YJF	60–90	125	0	0	1–3	5–6	0
18	YJF	90–130	130	0	0	1–2	8–10	0
19	AJF	60–100	90	0	0	1	–	0
20	AJF	100–120	120	0	0	3–4	–	0
21	OJF	180–200	150	0	0	0	2–3	0
22	AJF	90–120	90	0	0	15–20	30–40	0
23	OJF	120–160	95	0	0	1	4–5	0
24	AJF	300–450	125	115	18	50–60	–	30
25	AJF	180–200	105	60	16	40–50	150–160	0.02
26	AJF	210–240	105	56	16	15–20	40–50	0.01

*Farmers' estimate
†Study measurement

Table 4.2b Flooding and Sediment Deposition, Kalihati

Site No.	Physiographic Unit	Flood Depth and Duration: Normal Year Depth (cm)	Normal Year Duration (days)	1994 Depth (cm)	1994 Duration (days)	Sediment Deposition: Normal (cm)*	1988 (cm)*	1994 (cm)†
7	AJF	90–120	120	20	8	0	5–6	Trace
8	YJF	90–100	120	20	20	1–2	10–12	Trace
9	YJF	120–160	100	45	37	2–3	4–5	0
10	YJF	120–170	120	30	35	2–3	5–6	0
11	YJF	100–120	105	5	1	1–2	15–20	0
12	OJF	80–90	120	0	0	0	2–3	0
13	AJF	210–220	130	60	25	50–60	90–120	0.01
1	AJF	90–120	105	0	0	5–6	30–40	0
2	AJF	110–130	120	20	7	5–6	30–40	Trace
3	AJF	110–120	120	20	5	5–6	60–70	Trace
4	OJF	90–120	120	0	0	0	0	0
5	AJF	180–200	120	50	21	20–30	–	0.02
6	AJF	240–270	110	80	28	60–70	90–120	0.04

*Farmers' estimate
†Study measurement

Table 4.3 **Results of Sediment Samples with Area for Cloth, Mat, and Trap**

Sample No.	Type of Sample	Weight (kg)	Area (cm^2)	Sediment (ton/ha)	Depth (mm)
24	Cloth	99.40	2,209	4,500	300.0
25	Cloth	0.12	2,240	5.18	0.4
26	Cloth	0.08	2,193	3.45	0.2
13	Cloth	0.21	2,575	8.07	0.5
5	Cloth	0.27	2,567	10.44	0.1
6	Cloth	0.74	2,500	29.77	2.0
7	Trap	0.02	1,660	1.12	0.1
8	Trap	0.13	1,660	7.67	0.5
10	Trap	0.59	1,660	35.29	2.4
2	Trap	0.02	1,660	1.00	0.1
3	Trap	0.04	1,600	2.64	0.2
25	Mat	1.84	37,044	4.96	0.3
26	Mat	1.14	36,260	3.14	0.2
13	Mat	3.08	34,200	9.00	0.6
5	Mat	1.30	33,775	3.84	0.3
6	Mat	11.15	33,775	33.01	0.2

received significant amounts of sediment: site 8 at a rate of 7.67 tons/ha and site 10 at a rate of 35.29 tons/ha. Assuming a bulk density of 1.5 g/cm^2, those figures are equivalent to sediment thickness of about 0.5 mm at site 8 and 2.3 mm at site 10. However, field observation after the flood recession suggests that surface wash from higher land at site 10 may have outweighed the sediment deposited by river water at that site.

Cloths and mats. The six cloth and mat sampling sites set up in August were inundated by river water for 16–18 days. All six sites, 24, 25, 26, 13, 5, and 6, were on the Active Jamuna floodplain and received significant amounts of sediment. The thickness of the deposited sediment was .01–.04 cm, except for site 24, which received 30 cm. Table 4.3 shows the weight and associated depth (calculated) of the sediment deposited at each site. The most sediment was recorded at the infilled channel sites; site 24 received about 300 mm, and site 6 received about 2 mm.

4.1.2 Sediment Contents

The nutrient contents of sediment and topsoil samples collected at sampling sites are given below. Table 4.4 shows the reference levels against which nutrient contents were adjudged high, moderate, or low. Chapter 5 assesses the quantities of nutrients added by sediments in relation to the quantities extracted by crops.

Sediment traps. The analytical results for sediment samples collected in traps, presented in Appendix IV, Table IV.2a, are expressed as the mean value of three replicated samples. They show that the sediments had high levels of calcium, potassium, sulphur, iron, and manganese; moderate to high levels of phosphorus, copper, zinc, and nitrogen; and moderate levels of magnesium and boron. In general, finer sediments at lower sites contained more nutrients than coarser ones at higher sites.

Cloths. Except at one site (24), sediments deposited on cloths (Table IV.2b in Appendix IV) had high contents of calcium, iron, sulphur, and manganese, high to moderate contents of potassium, nitrogen, phosphorus, copper, and boron, moderate contents of magnesium, and low contents of zinc. The coarse-textured sediments at site 24 had low contents of all nutrients except calcium (high), and of magnesium, sulphur, and boron (moderate).

Mats. The sediments deposited on mats (Table IV.2c in Appendix IV) had nutrient contents similar to those of sediments deposited on the cloths. At all sites, the contents of calcium, sulphur, iron, and manganese were high; potassium, nitrogen, and boron were between moderate and high; and

Table 4.4 **Approximate Values of Plant Nutrients Used to Interpret Soil Test Results**

Element	Low (≤)	Medium	Optimum
N (ug/g soil)	75	76–150	151–300
P (ug/g soil)	12	12–25	26–75
S (ug/g soil)	12	13–25	26–75
B (ug/g soil)	0.2	0.21–0.50	0.51–4
Cu (ug/g soil)	1	1.1–3	3.1–10
Fe (ug/g soil)	20	21–40	41–200
Mn (ug/g soil)	5	5.1–10	11–50
Zn (ug/g soil)	2	2.1–4	4.1–18
Ca (meq/100 g soil)	2	2.1–4	4.1–18
Mg (meq/100 g soil)	0.8	0.81–2	2.1–9
K (meq/100 g soil)	0.2	0.21–0.4	0.41–1.5

Source: SRDI (1991)

magnesium and copper were moderate. Phosphorus contents varied widely between low and high.

4.1.3 Nutrient Contents of Topsoil Samples

In both study blocks (Sharishabari and Kalihati), topsoils in all physiographic units had similar nutrient levels. Analytical data are presented by physiographic unit and topographic position in Tables IV.3 and IV.4 (Appendix IV). The results are expressed as the mean value of three replicated samples. The findings are reviewed by physiographic unit below. No topsoil samples were taken from the Old Brahmaputra floodplain, but data for a single profile from a floodplain basin site, reported in Section 4.1.4, are discussed below for comparison with Jamuna floodplain topsoils.

Active Jamuna floodplain. Calcium and manganese contents of topsoils on this floodplain were high, boron contents were moderate, and phosphorus and sulphur contents were moderate to low. Potassium, nitrogen, and zinc contents were low at almost all the sites. Contents of iron, copper, and magnesium varied widely from low to high. Organic matter contents ranged between 0.3 and 1.3 percent, and pH values ranged between 6.3 and 7.7.

Young Jamuna floodplain. Topsoils on this floodplain had high amounts of calcium, iron, and manganese. Magnesium and copper levels were high in most places but moderate at some sites. Phosphorus contents were moderate to low, and potassium, nitrogen, sulphur, and zinc levels were low. Boron levels were mainly moderate. Organic matter contents (0.8–1.4 percent) were slightly higher than on the active floodplain, but pH values were similar (6.3–7.6).

Older Jamuna floodplain. Topsoils on this floodplain had high amounts of calcium, magnesium, iron, and manganese similar to those on other floodplains. Phosphorus and boron levels were moderate, and potassium, nitrogen, sulphur, and zinc levels were low. Levels of copper varied from moderate to high. Generally, organic matter contents on this floodplain (1.0–2.5 percent) were higher than on the Active and Young Jamuna floodplains, and pH values were lower (6.3–6.8).

Old Brahmaputra floodplain. The topsoil example from this floodplain comprised two layers. Combining and averaging the data for these layers showed them to have an organic matter level (1.9 percent) similar to that in the depression sample (site 4) from the Older Jamuna floodplain but a lower pH (5.6). Calcium and magnesium levels were high and potassium levels were moderate.

4.1.4 Nutrient Contents of Soil Profile Samples

Twelve soil profiles were described and sampled to a depth of 1.5 m to determine the physical, morphological, and chemical characteristics of the study area's major soils. Tables IV.5 and IV.6 (Appendix IV) present the analytical data for the top three layers of all profiles sampled during the study. In addition, Appendix II provides detailed descriptions and analytical data for two representative profiles from each of the three physiographic units on the Jamuna floodplain and for a typical basin soil from the Old Brahmaputra floodplain. Data for the latter profile were extracted from the Tangail reconnaissance soil survey report (SRDI 1967a); only data for OM, pH, Ca, Mg, and K are quoted for this profile because other nutrient contents either were not determined or were determined using different methods.

The organic matter contents of Jamuna floodplain topsoils generally were low (0.5–1.1 percent). The exception, site 12, a depression site, had 2.5 percent, which is similar to the amount quoted for the Old Brahmaputra floodplain soil. In most profiles, organic matter contents decreased with depth.

Topsoils of the Active and Young Jamuna floodplains were mainly neutral to mildly alkaline in reaction, whereas those of the Older Jamuna floodplain soils were moderately acid, and that of the Old Brahmaputra was strongly acid in the surface layer. In most Jamuna floodplain soils and the Old Brahmaputra floodplain soil, subsurface layers were near-neutral to mildly alkaline, but they were slightly or moderately acid in the site 12 profile.

Calcium levels in virtually all soil horizons were high. Magnesium levels were more variable: mainly high on the Young and Older Jamuna floodplains and the Old Brahmaputra floodplain, but ranging between low and high on the Active Jamuna floodplain. Potassium levels were moderate in the Old Brahmaputra floodplain soil but, together with zinc, they were low in all soil horizons in other physiographic units. Phosphorus and sulphur contents were mainly low, but they were moderate in topsoils at a few sites; levels generally decreased with depth on the Young and Older Jamuna floodplains, but they were more variable on the active floodplain. Nitrogen levels were moderate at some of the lower sites (21, 12, 2) but low elsewhere.

Soils of the Older Jamuna floodplain had high iron and manganese contents, but amounts varied widely between low and high in other physiographic units. Copper and boron levels were moderate or high in most soil horizons.

4.1.5 Dissolved Nutrients

Water samples were collected from rivers and six sampling sites to determine the quantities of dissolved nutrients. These sampling sites (24, 25, 26, 13, 5, and 6) were inundated more deeply by river water and for a longer period than other sites. Table IV.7 (Appendix IV) presents the analytical results, expressed as the mean value of three replicated samples.

River water was higher in total dissolved solids (TDS), calcium, magnesium, and manganese than the surface water at the sampling sites, but boron and iron contents were lower in river water. Potassium and phosphorus levels generally were higher at sampling sites than in the river water, and they were higher at the Sharishabari sites than at Kalihati. Contents of calcium, magnesium, potassium, copper, iron, and manganese were slightly higher in Jamuna River samples than in those taken from the Dhaleswari River.

River water was near-neutral in reaction, whereas water from the Sharishabari sites was mildly alkaline and that from the Kalihati sites was moderately acid.

Water samples generally had much higher contents of calcium, magnesium, and potassium, and much lower contents of other nutrients, than sediment samples collected at the same sites. The exception was site 6, where boron was slightly higher in water than in sediment. The magnitude of the differences between the data for water and sediment samples, and the fact that contents of cations are consistently higher and those of other nutrients are consistently lower (with the exception noted), suggest incompatibility between the methods used rather than actual differences in nutrient contents.

4.2 Radiocesium and Textural Analyses

Results from the cesium laboratory analyses are presented in Figure IV.1 and Table IV.8 (Appendix IV). In general, activity profiles from the Active Jamuna floodplain revealed detectable ^{137}Cs levels to greater depths than observed in the Older Jamuna floodplain. Silt- and clay-size material typically comprised about 90 percent of the samples (sand percentages usually < 10 percent). The three surface samples, consisting of fresh material from the 1994 flood, revealed a good relationship between ^{137}Cs and percent clay (Figure 4.4), indicating the importance of grain size in controlling observed ^{137}Cs activities. Atmospheric fallout levels of ^{137}Cs were determined from cores collected in the forested Madhupur Tract (sites 35, 36, and 60). Additional "background" cores were collected from the Old Brahmaputra floodplain, an area where little or no turbid-water flooding is occurring today.

The consensus of these cores was that Cs penetration depths of about 10 cm could be attributed to the combined effects of diffusion, bioturbation, and plowing (Figure IV.1, Appendix IV). The penetration depth method (see below) considered ^{137}Cs below this depth to be accumulation. Exceptions to the 10-cm mixing depth (sites 36 and 60) are

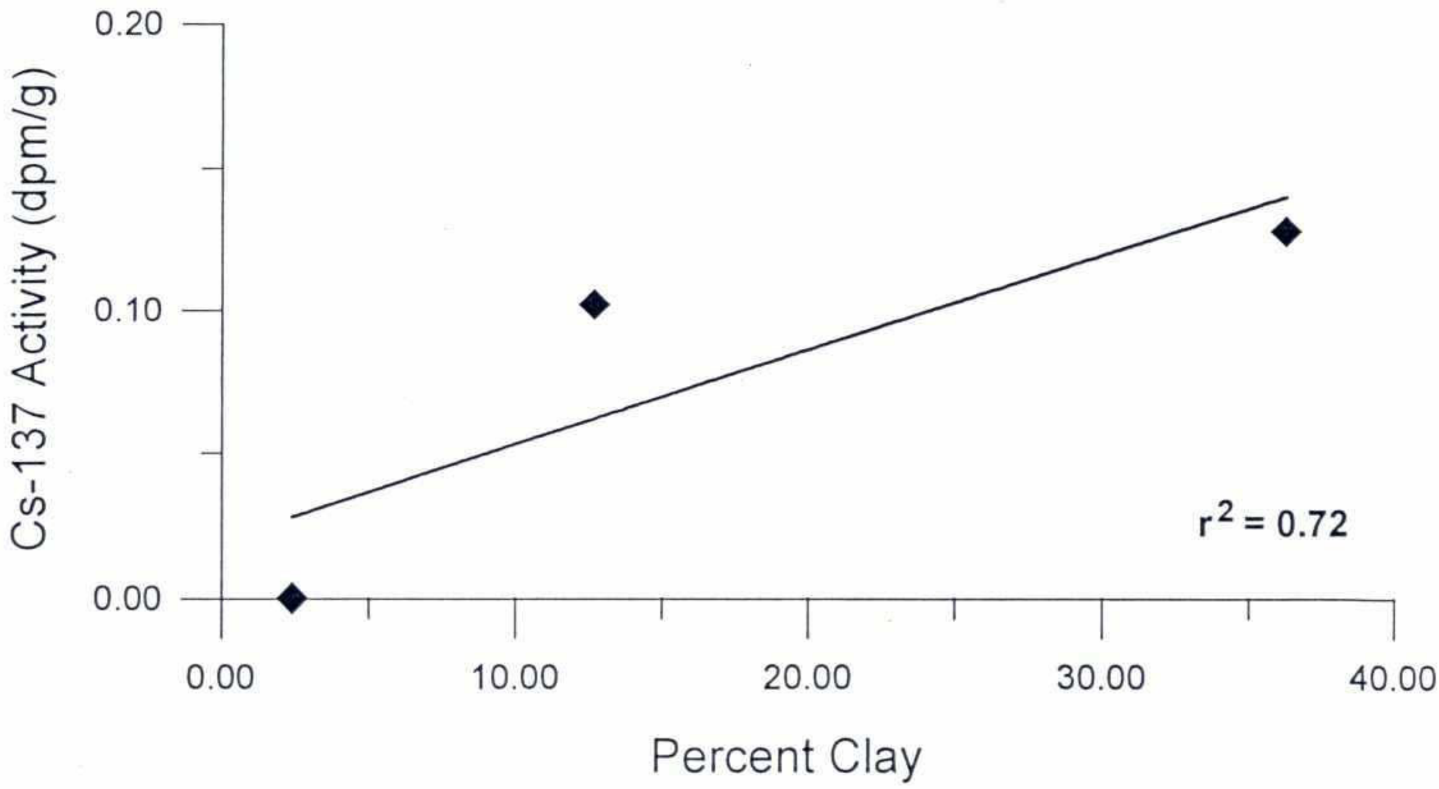


Figure 4.4 Percent Clay Versus ^{137}Cs Activity (dpm/g)

Table 4.5 Sediment Accumulation Rates Based on Excess Penetration (>10 cm) of ^{137}Cs

Site Number	Min. Cs Depth	Max. Cs Depth	Min. Accumulation Rate (cm/yr)	Max. Accumulation Rate (cm/yr)
12	20	22	0.26	0.32
27	53	59	1.13	1.29
28	41		0.82	
29	42		0.84	
30	41		0.82	
11	158		3.89	
31	40	42	0.79	0.84
32	37	39	0.71	0.76
33	70	81	1.58	1.87
24	60		1.32	
23			Bag Samples	
21	0	20	0.00	0.26
34	12	14	0.05	0.11
35	8	10	Soil	Soil
36	20	30	Soil	Soil
37	130		3.16	
38	45	60	0.92	1.32
8	20	130	0.26	3.16
39	0	10	0.00	0.00
40	0	15	0.00	0.13
41	0	15	0.00	0.13
42	15	30	0.13	0.53
43	0	15	0.00	0.13
44	0	18	0.00	0.21
45	15	30	0.13	0.53
46	0	15	0.00	0.13
47	0	10	0.00	0.00
48	15	30	0.13	0.53
49	15	30	0.13	0.53
50	0	15	0.00	0.13
51	15	30	0.13	0.53
52	0	15	0.00	0.13
53	0	15	0.00	0.13
54	15	30	0.13	0.53
55	15	20	0.13	0.26
56	15	30	0.13	0.53
57	0	10	0.00	0.00
58	10	18	0.00	0.21
59	0	12	0.00	0.05
60	20	30	Soil	Soil
61	50		1.05	
74	19	29	0.24	0.50

attributed to the effects of earthworm activity observed at those sites. This figure is further validated by the fact that < 10 cm ^{137}Cs penetration was observed in many of the Jamuna floodplain sites (i.e., zero accumulation).

4.2.1 Normalization of ^{137}Cs Activities

By observing the relationship between the percentage of sand in three surface samples deposited during the 1994 flood season and their activity, it was concluded that sand carries no significant ^{137}Cs. Therefore, the observed activities were normalized to the silt+clay (mud) fraction only. The observed activity was multiplied by the inverse of the mud fraction:

Activity normalized to mud fraction = Observed activity × (1/mud fraction).

To remove the effects of grain size on observed activity, the sand-normalized activity was multiplied by a "correction factor." This factor was derived from the three surface samples mentioned above. A regression was run on these three samples for sand-normalized activity versus percent clay (Figure 4.5). This function was considered to show the "ideal" activity in relation to the percentage of clay in a sample. The ideal activity for the percentage of clay in each sample was divided by the ideal activity for 30 percent clay; the inverse of this ratio is the correction factor:

Grain-size-normalized activity = Sand-normalized activity × Correction factor

Correction factor = 1 /(Ideal activity/Ideal activity for 30 percent clay).

For each sample, ideal activity was calculated from the linear equation given by the regression:

$$y = mx + b$$

Where:
y = Ideal activity
m = 0.0033
x = Percentage of clay
b = .02

4.2.2 Radiocesium Inventories

The ^{137}Cs inventory is defined as the total, vertically integrated activity per unit area (dpm/cm^2) at a site and is calculated by multiplying the activity by the bulk density and length of each interval, then summing the results:

Inventory = Σ (Activity × Bulk density × Length of interval) for all sample intervals in a site

Two figures for ^{137}Cs inventory are given: the inventory of raw activity for an assumed bulk density of 1.35 g/cm^3 (this value applies only to the Cs analysis, for all other analysis the assumed bulk density was 1.5), and the inventory of grain-size-normalized activity for an assumed bulk density (Table IV.8).

Some sites had sample intervals for which activity was not measured. An averaging technique was used to calculate the inventory for these sites. The interval was split into two equal lengths. The top length's inventory was calculated using the activity of the interval directly above it, and the bottom length's inventory was calculated using the activity of the interval directly beneath it.

4.2.3 Accumulation Rates and Inventories

Sediment accumulation rates were calculated for each of the ^{137}Cs sites from the observed excess (i.e., >10 cm) penetration depths (Table 4.5). Accumulation rates were calculated by taking the excess penetration depths and dividing by the time since first significant input, 38 years. In some cases, only minimum rates could be given as the cores did not recover complete ^{137}Cs profiles. Minimum and maximum accumulation rates are reported based on the uncertainty introduced by the sampling interval. In general, rates were up to 4 cm/yr in the active braid belt and low (<1 cm) or negligible in the older floodplain, with some local exceptions (see discussion in Chapter 5). In addition, inventories were typically higher in areas with higher accumulation rates.

Table 4.6 **Sediment Deposition by Physiographic Unit**

Physiographic Unit	Total Sediment: Weight (metric tons)	Total Sediment: Area (ha)	Mean Annual Rate: Weight (metric tons/ha)	Mean Annual Rate: Depth (mm)
Active Jamuna Floodplain	5,054,515	22,895	221	11.5
Young Jamuna Floodplain	5,291,261	41,577	127	8.1
Older Jamuna Floodplain	9,514,512	83,901	113	7.1
Old Brahmaputra Floodplain	9,379,594	84,629	111	6.7

To better evaluate the relationship between ^{137}Cs inventories and sediment accumulation rates, plots of raw and grain-size-normalized inventories versus sediment accumulation rates were produced (Figure 4.5). Linear regression of these plots revealed a moderately low r^2 value (.51) for the raw inventories. Using normalized inventories produced a significantly better fit (r^2 = .77), suggesting that the approach used in this study to apply grain-size corrections to account for spatial heterogeneity of sediments is reasonable.

4.3 GIS Mapping Modelling Results

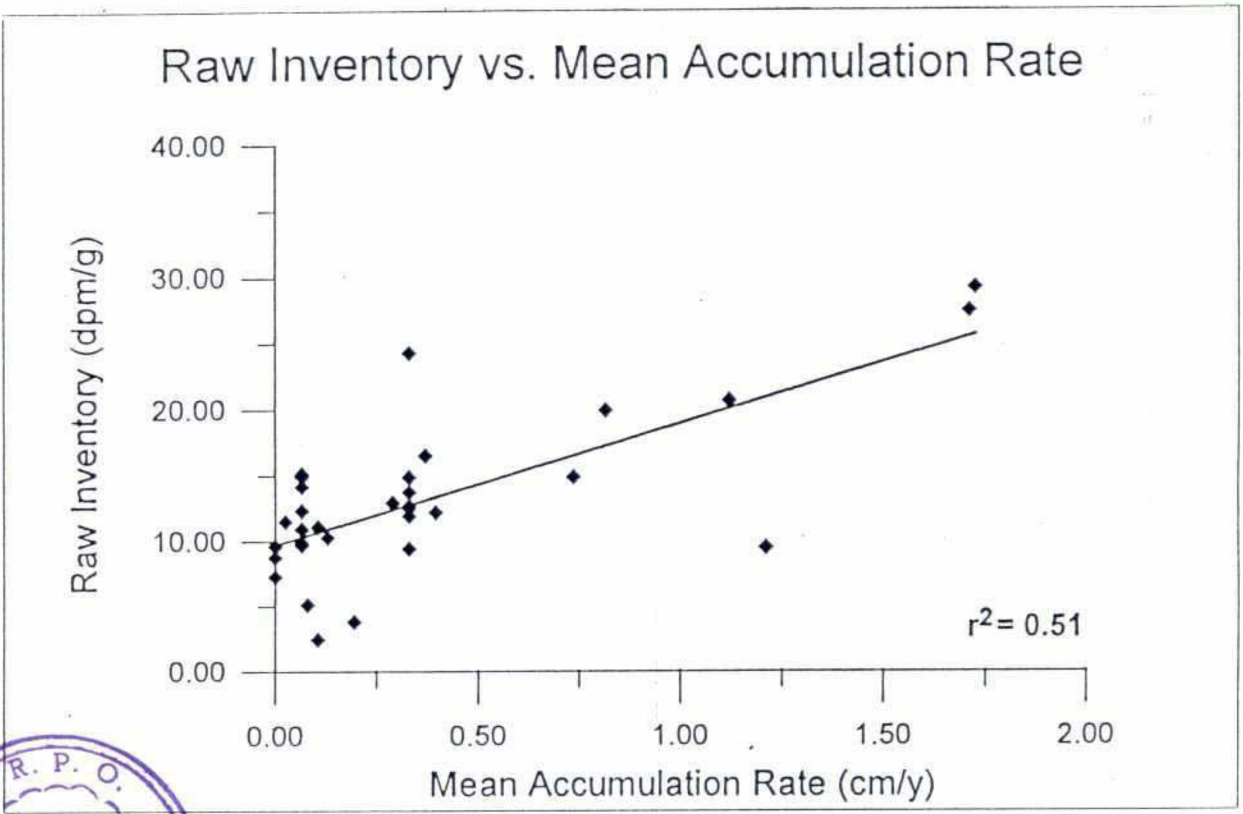
The GIS model for mapping regional sedimentation regimes was run as described in detail in Section 3.4. GIS "map algebra" was used to implement the model using as variables the analytical by-products of the primary data theme maps: distance from sediment source, estimates of flood depth, physiographic regions, spatial-temporal changes in the Jamuna River bankline, and sedimentation in an extreme flood. Geographically coincident pixels from each of these map variables were mathematically overlaid to calculate the corresponding pixel values for the output GIS map. Field data were also used to construct a function predicting annual sedimentation rates with respect to distance from sediment sources. Annual rates as measured by the ^{137}Cs inventories laid the mathematical foundation for the distance function, while the rates reported by farmers were used as a basis for determining minimum rates for each physiographic unit in the study area. Figures 3.16 and 3.17 are concise summaries of the model. The model yields maps of current annual sedimentation rate and cumulative sediment deposition over the past 40 years (1954–1994) in a digital map format.

4.3.1 Annual Sediment Deposition Rate

Annual sedimentation rate maps generated by the GIS model are shown for the entire study area in

Table 4.7 **Sediment Deposition Rate by Study Block**

Study Site	Total Sediment: Weigh (metric tons)	Total Sediment: Area (ha)	Mean Annual Rate: Weight (metric tons/ha)	Mean Annual Rate: Depth (mm)
Kalihati	1,044,374	8,649	121	7.5
Sharishabari	1,457,798	5,529	264	13.6



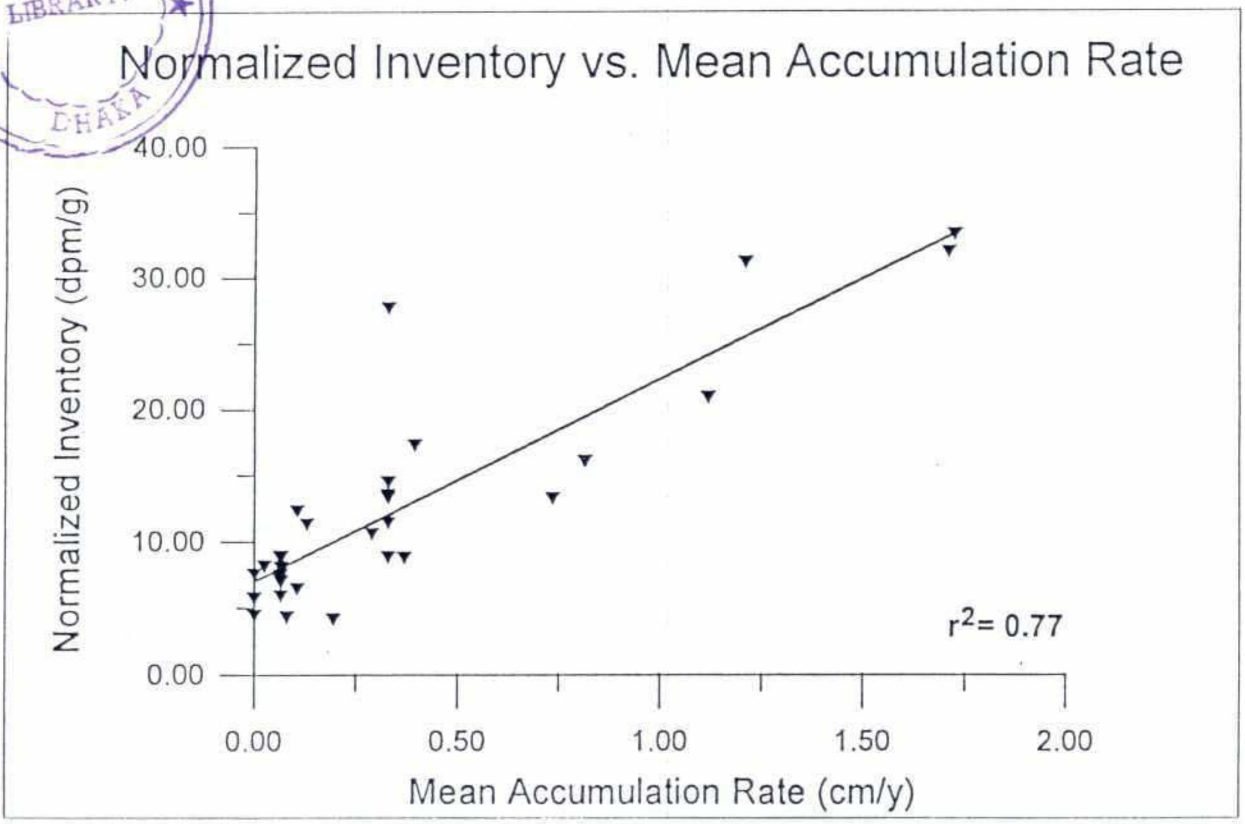


Figure 4.5 **Mean Accumulation Rate Versus Raw Inventory and Normalized Inventory**

Figure 4.7 and for each study block in Figure 4.8 Rates as determined by the GIS model for the study area range from 0 to 74 mm/year with an average rate of 7.6 mm/year. The calculation of the weight of the sediments deposited in one year was based on these rates and an assumed sediment bulk density of 1.5 g/cm^3. The total estimated sediment weight for the study area was 29.3 million metric tons. The distribution of the sediment and the area covered is shown in relation to the annual rates predicted by the model in Figure 4.8. Note that the low rates account for a large proportion of the study area but relatively little of the total sediment deposits, and vice versa. For example, areas annually receiving 10 mm or less of sediment account for only 25 percent of the total sediments but cover 75 percent of the study area. Also noteworthy is the relationship between sediment weight and proximity to sediment source. According to the model, approximately 84 percent of the sediment deposited annually is within 0.5 km of a sediment source, but only 27 percent of the study area is within this distance.

The same statistics were calculated for the study area on the basis of physiographic unit (Figure 3.10) using GIS techniques, and are shown in tabular form in Table 4.6. The physiographic units in the table are ordered from most to least dynamic moving from left to right. In general, the total amount of sediment deposited is relatively high and the area covered is relatively low for the two most active physiographic units. In other words, as would be expected by their definitions, the Active and Young Jamuna receive more sediments per hectare than the less active Older Jamuna and Old Brahmaputra floodplains. Note that the Active Jamuna floodplain receives roughly twice as much sediment per hectare as the Old Brahmaputra floodplain. This relationship is also reflected in the mean depths for these physiographic units.

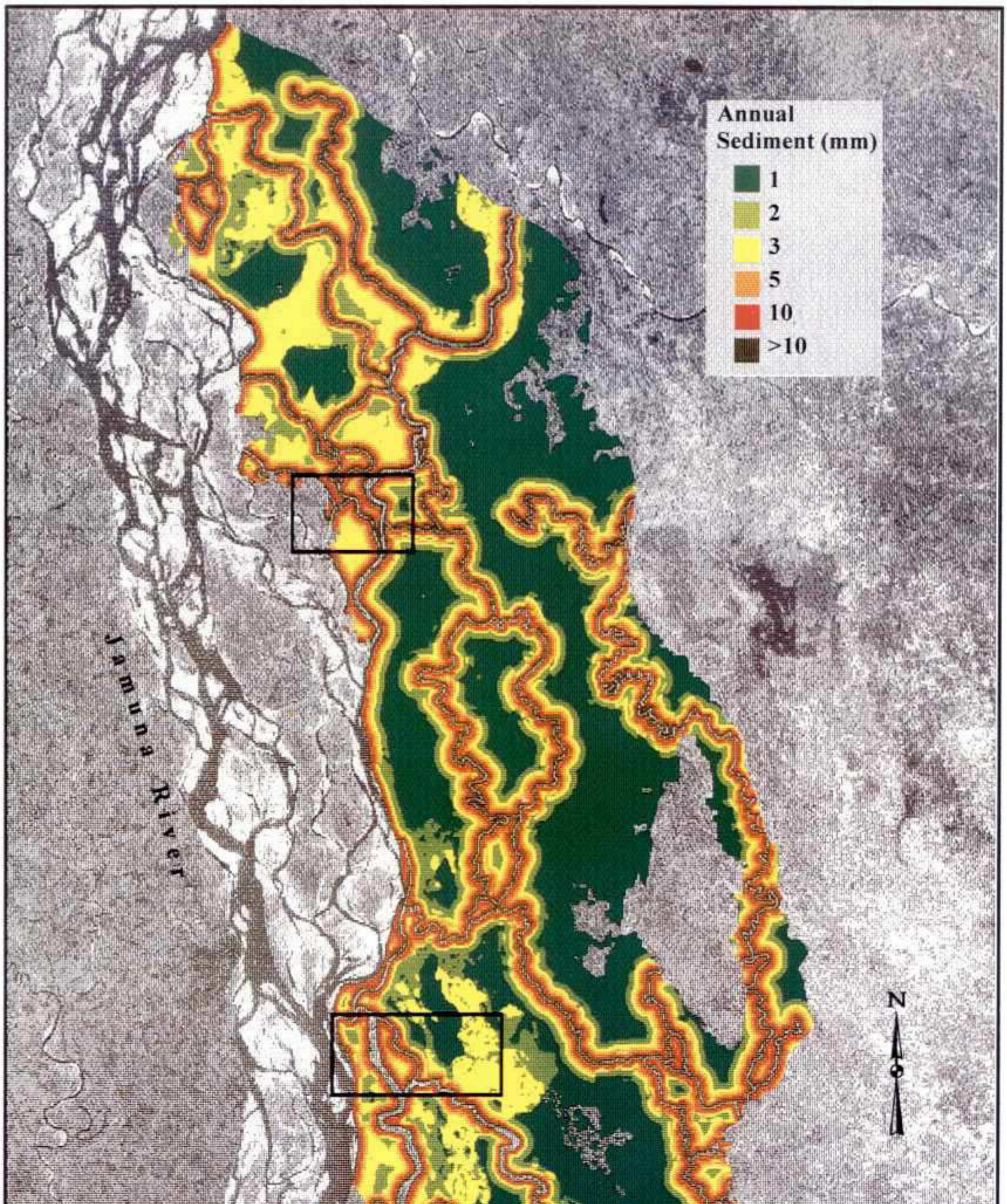
Study block statistics on annual rates, sediment quantities, and areal coverage were also tabulated as shown in Table 4.7.

Estimates of the quantity of sediment deposited in the Sharishabari block are relatively high (264 t/ha), and the block consequently has a high mean annual rate of 13.6 mm. This is in part due to the fact that 60 percent of the block consists of Active Jamuna floodplain. The block also has little flood-free (F0) land. In the Kalihati block, on the other hand, the mean annual rate of 7.5 mm is nearly identical to the average for the entire study area. The Kalihati block is dominated by Young Jamuna floodplain (64 percent) and a contains a significant proportion of Older Jamuna floodplain (13 percent). There is also a considerable amount of flood-free (F0) land. The combined effect of these factors resulted in a large share of low annual rates in the model falling between 1 and 3 mm/year.

The distribution of annual rates can be visualized in their geographic context using Figure 4.7. Estimated rates greater than 10 mm (shown in brown) constitute only a small portion of the mapped area. The bulk of the study area (75 percent) clearly is composed of rates less than 10 mm. The relatively higher rates (shown in brown and red) only occur close to rivers and *khals*. The block maps (Figure 4.9) show a close-up view of this relationship. Here, linear bands of a single sedimentation rate encase the river channels. These layers are the expression of the distance function component of the model, i.e., as distance from the river increases, the annual rate decreases. The rate was assumed to level off at a base level as discussed in Section 3.4.

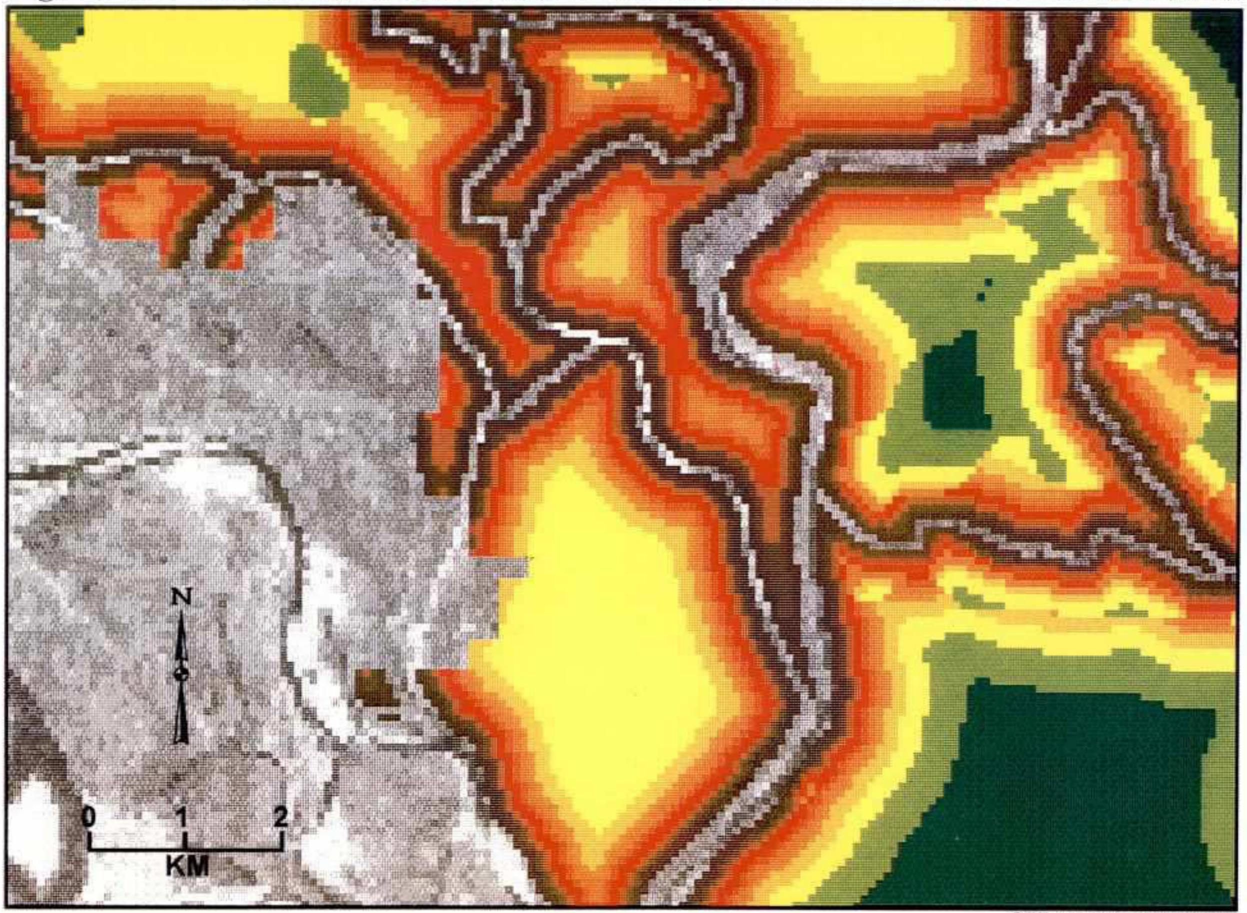
The areas in green or yellow on the GIS maps indicate where the physiography-based minimum rates were imposed by the model leveling off the function at 1 or 3 mm. They are generally located at the periphery of high-sedimentation zones close to the river and in the more remote floodplains. The yellow and light green colors in the remote floodplains largely represent areas where the minimum rate of 3 mm for the Active and Young Jamuna floodplains was imposed. This has mainly occurred in the northwest and southwest portions of the study area adjacent to the Jamuna River and in the Jhenai River basin in the northeast. The light green areas in particular indicate areas where F0 inundation land types (minimal flooding) diminished the rate in accordance with the model (by 50

Figure 4.7: GIS Sedimentation Model Result for Study Area

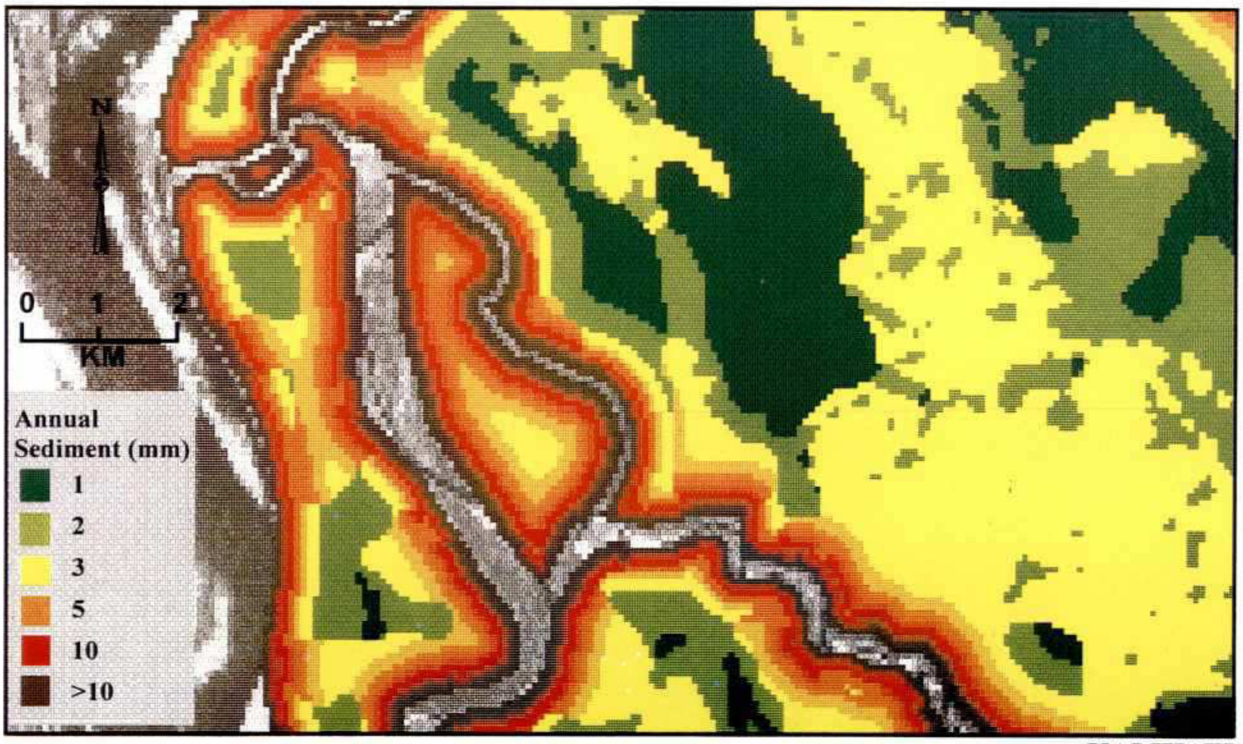


b3

Figure 4.8: GIS Sedimentation Model Result, Sharishabari and Kalihati Blocks

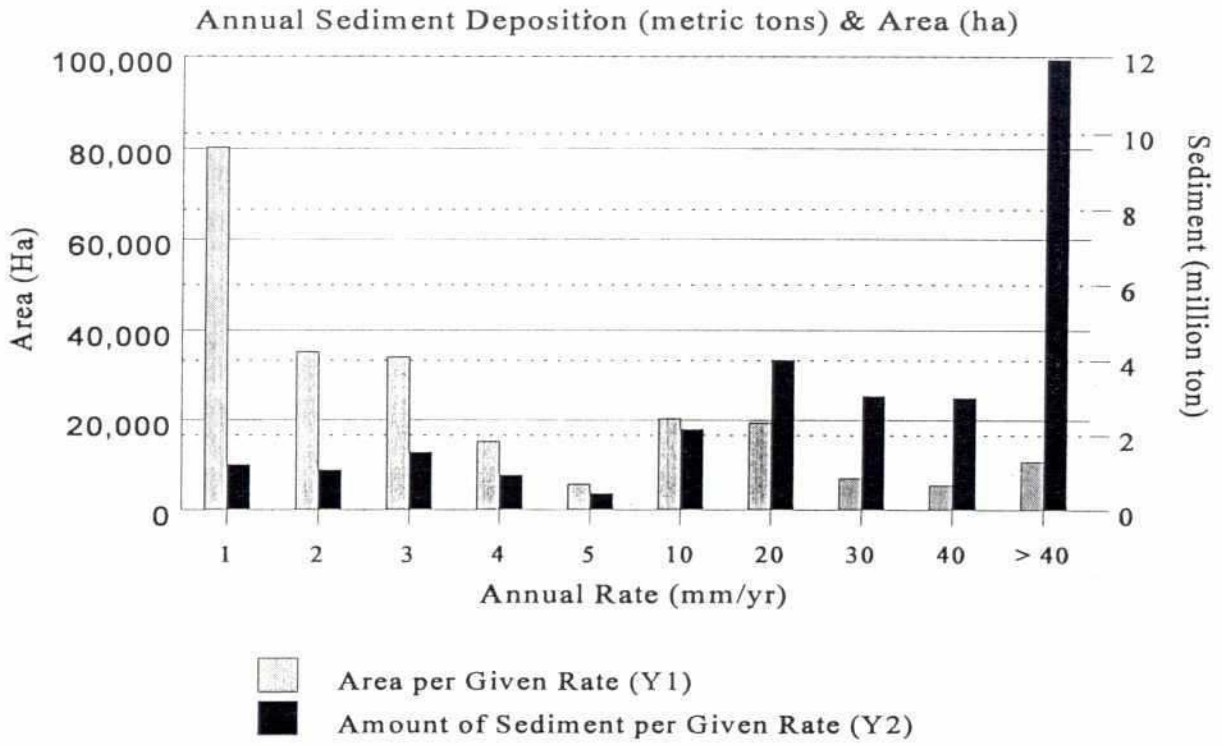


SHARISHABARI



KALIHATI

Figure 4.9 GIS Model Results: Amount of Sediment and Area for Various Rates



percent). The controlling variable for the dark green areas in the remainder of the remote floodplains was the minimum rate for the Older Jamuna and Old Brahmaputra floodplains. Speckling, in all categories on the map, is an effect of the non-flooded areas and non-sediment floodwaters in the 1987 flood image map. The model reduces rates by 50 percent for these 1987 map categories.

The large blank triangular area in the east central portion of the map is the Madhupur Tract, which is considered flood-free in the model. All other blank areas (no sedimentation) on the rate map are a combined effect of the older physiographic units, F0 inundation land types, and/or non-flooded areas and non-sediment floodwaters as indicated by the 1987 flood map.

4.3.2 40-Year Cumulative Sediment Deposition

A map of cumulative sediment deposition over the 1954–1994 period was also generated by the GIS model. This period corresponds with that of the ^{137}Cs analysis of soil samples for determination of sediment accumulation rates. Cumulative deposition for the period was calculated by multiplying the annual rate map by the age of the land to adjust for land age. Recall that the land age map is a product of historic changes in the location of the Jamuna River left bank (Figure 3.13).

The land age factor represented by this map only affected a small portion (5.4 percent) of the study area. The areas affected include three lobes on the left bank of the Jamuna: in the northwest, west of the Sharishabari block, and west of the Kalihati block. In these places, riverine accretion formed land sometime between 1953 and 1973, making it less than 40 years old. Therefore, except in the three areas mentioned above, the same general numerical distributions and spatial patterns are exhibited as with the rate map.

Forty-year cumulative deposition, as estimated by the GIS model for the study area, ranges from 0 to

296 cm with an average thickness of 29.5 cm. The total estimated weight of sediment deposited in the study area is 1,135 million metric tons. Regions receiving 40 cm or less in the 40-year period accounted for 26 percent of this sediment in 75 percent of the study area. Conversely, approximately 83 percent of the sediment was deposited within 0.5 km of the sediment sources, accounting for only 26 percent of the total study area.

Chapter 5

ASSESSMENT OF RESULTS

5.1 Determinants of Sedimentation

5.1.1 Sedimentation Zones

The sedimentation rates compiled from farmer interviews and by calculating excess ^{137}Cs penetration suggest the strongest correlations result from a classification based on physiography. The existing soil divisions of Active, Young, and Older Jamuna, and Old Brahmaputra floodplains, in effect, are categories based on soil age. In a sedimentation sense, well-developed soil profiles (i.e., old age) cannot occur where there is relatively rapid sediment input. These categories therefore are a convenient way to summarize spatial differences in Jamuna floodplain sedimentation.

Several conclusions can be drawn from the physiographic sedimentation data in Tables 5.1 and 5.2. Where the data types overlap, they tend to agree. This suggests that farmer interviews are a useful method of determining relative sedimentation rates in a floodplain area. At 19 sites, Cs rates were <1 cm/yr and, in every case, the farmers also reported <1 cm/yr (generally 0) at the same site. Because Cs methods are dependent on depth of coring, farmer interviews provide the only information on sites with extreme sedimentation rates (>4 cm/yr). Farming in Bangladesh requires close observation of the conditions on a very small (typically <200 m^2) plot. Each farm plot serves as a sedimentation monitoring site not unlike the plots deployed with mats and traps by the present study. Unfortunately, the limited data from the sedimenta-

Table 5.1 Sediment Accumulation Rate and Grain Size Data for Cs Cores from Each Floodplain Region

Floodplain Region	Number of Cores	Average (range) Sediment Accumulation Rate (cm/y)*	Downcore-Averaged Sand:Silt:Clay Percentage
Active Jamuna	1	>1.32	2:82:16
Young Jamuna	14	1.24 (0->3.89)‡	6:64:30
Older Jamuna	20†	0.29 (0-1.05)	5:51:44
Old Brahmaputra	3	0.15 (0-0.53)	5:43:52

* average calculated as max.-min./2; range calculated from lowest minimum to highest maximum; minimum value used in cases where Cs found to bottom of the core

† does not include core no. 27 from the extreme southern field area (>1.05 cm/y; 1:46:53 percent) that may be influenced by overbank flooding from the southern Dhaleswari offtake

‡ includes six cores where Cs was found to the bottom of the core (minimum accumulation rate)

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Table 5.2 Summary of Farmer-Reported Sedimentation Rates for Average Years and in the 1988 Flood

Floodplain Region	Average (range) of the Mean Flood Sedimentation Rate (cm/y)	Mean Year Number of Sites	1988 Average (range) Sedimentation Rate (cm/y)	1988 Number of Sites
Active Jamuna	14 (0–70)	26	41 (4–160)	23
Young Jamuna	2.1 (0–5)	21	27 (2–120)	21
Older Jamuna	0.1 (0–1)	16	2.1 (0–5)	14
Old Brahmaputra	0 (0)	3	2.3 (1–4)	3

tion plots (because of the low 1994 flood) did not permit their comparison with farmers' data.

The data in Tables 5.1 and 5.2 show a strong correlation between sedimentation rate and floodplain age. In general, only in the Active and Young Jamuna floodplains is significant sedimentation taking place. However, Figure 3.15 demonstrates that this is a function of distance from a source, including distributaries and even *khals*. Thus, significant sedimentation can occur in the older floodplain areas immediately adjacent to a distributary or *khal*. Since these features migrate across the floodplain over time, this is an important means of sedimentation (and creating relief; see Section 5.1.2) in older areas. The highest observed sedimentation rates (from farmer data) are on the natural levee and splay deposits (up to 160 cm/yr). As sedimentation decreases with soil age and distance from the source, grain size also decreases. Table 5.1 demonstrates a progressive decrease in the silt:clay ratio with increasing distance from sediment sources. This relationship has been observed in other systems (see Figure 1.2). It results when coarser material settles near the source, leaving only fine-grained material to be deposited in stagnant distant (lower elevation) areas.

The stages in the progressive evolution of sedimentation at any site on the floodplain might be as follows:

(1) Lateral river migration creates new land.

(2) Rapid vertical accretion (decimeters per year) occurs in natural levee/splay setting (Active Jamuna).

(3) As the river migrates away, sedimentation decreases to cm/yr (Young Jamuna). (Plus possible partial erosion of sequence, deposition of channel sand/levee sequence with distributary migration across site.)

(4) Soil develops rapidly as sedimentation decreases to negligible except during large floods (average rate, mm/yr) (Older Jamuna). (Plus possible partial erosion of sequence, deposition of channel sand/levee sequence with distributary migration across site.)

(5) Backswamp/flood basin forms with virtually no sediment input or peat accumulation.

The sequence may reverse at any stage in the cycle if the Jamuna migrates back across the floodplain. The amount of time a site spends in each stage depends upon the lateral migration rates of the river and its distributaries.

5.1.2 Topographic Controls

In some cases, elevation changes on the floodplain are a direct result of the sedimentation process. For example, natural levee and crevasse splay deposits on the active floodplain may be elevated several meters above the surrounding floodplain. Sedimentation rates observed in this study, and in other river systems (see Mertes 1994, for example), typically are decimeters to meters per year for such areas—an order of magnitude or more above those in more distant areas. Hence, elevated features on the active floodplain are created by rapid sedimentation on time scales of a few years to decades. Similarly, low-elevation *beel* areas result, in part, from negligible sedimentation.

However, the sedimentation/elevation link is more complicated than that. Elevation also is a *barrier* to the distribution of sediment across the floodplain. For example, a natural levee/splay complex can become progressively more distant from the river if the channel migrates. The probability of this happening is particularly high in an unstable, young, braided river like the Jamuna. As the active floodplain moves away from the feature, sedimentation rates decrease exponentially with distance and it becomes a natural "embankment" that is exposed in all but the highest floods. In this way, natural levees and splay deposits produced by vertical accretion are indistinguishable from elevation on the floodplain produced by lateral accretion due to channel migration. Point bars (scroll, lateral, side) generated at the river-land interface, and levees generated immediately landward of the interface, are active floodplain features that become barriers to sedimentation as the channel moves away.

The strong relationship between sedimentation rate and distance from the river source means that these barriers to sediment delivery rapidly decrease in significance with distance from the river. For instance, in areas less than about 1 km from the river channel, where sedimentation rates are cm/yr, any increase in the distance sediment must traverse (by diffusion or advection) due to diversion around a barrier will significantly affect sedimentation rates behind the barrier. In more distant areas, an incremental increase in the distance travelled will be far less significant as the sedimentation rate curve becomes asymptotic (see Figure 3.15). Orientation of the feature relative to the direction of overbank flow also will play a role in this.

The presence of distributary (e.g., Dhaleswari, Jhenai, etc.) and tertiary channels (*khals*) extend this process far into the Jamuna floodplain. This study has shown that these features, too, have "active floodplains" that create raised levees through rapid vertical accretion and scroll bars through lateral accretion. Migration of these higher-order channels across the floodplain, and the reworking of older examples, produces a complex network of raised features of various elevations and orientations. This suggests that some low-elevation *beel* areas (the shape of others implies that they form as cut-off channel bends) form when a section of "old" floodplain is isolated in more recently active floodplain characterized by areas of raised topography. That is to say, negligible sedimentation in *beels* results from their being cut off from sedimentation sources by areas of high elevation produced by those sources. Their low elevation subjects them to deep flooding by rainwater and rising groundwater tables, rather than flooding by turbid water.

The foregoing argument also says that the "age" of any area of the floodplain is important for sedimentation and soil development (see Section 1.4). This implies that local redistribution of sediment is taking place on the floodplain, and therefore, older areas of the floodplain (i.e., areas where greater time has passed since reworking by migration of the Jamuna or higher-order channels) have less relief. Redistribution of fine-grained sediment by down-gradient rainwater runoff when the floodplain is not flooded certainly is occurring. Sediment redistribution from high areas to low ones likely is occurring as well because of intensive farming, which tends to "flatten-out" floodplain relief. This relationship between floodplain age and relief can be observed in the different physiographic units of the field area: there is a progressive decrease in relief from the Active Jamuna floodplain to the Young and Older Jamuna floodplains to the Old Brahmaputra floodplain.

This process potentially has implications for interpreting sedimentation rates from the Cs data. Radiocesium analysis is unable to differentiate between new sediment input from the Jamuna (or smaller distributaries) and local sediment accumulating in low-elevation areas. In an attempt to measure the importance of redistribution, this study collected seven cores (sites 40–46) from a ~1 km^2 section of the Kalihati block where there is 2–3 meters of relief. Results did not measure significant redistribution; in fact, the highest sedimentation rates were in high areas, a reflection of their recent deposition by distributaries. High and low elevation cores collected in other sites (31–33, 52, and 53) show no trend attributable to redistribution. This indicates that redistribution rates fall within the error bars of the sampling interval (<2–3 mm/yr).

5.1.3 Infrastructure Controls

The map in Figure 3.7 indicates the current location of roads and embankments in the study area. Embankments have been constructed at various times since the late 1960s, so it is difficult to assess the changes from ^{137}Cs accumulation rates integrated since the 1950s. However, even in areas isolated from the river by embankments (the term used hereafter to refer to flood embankments, roads, or railways), the supply of turbid water likely is not completely removed. The policy along the left bank has been to control flooding from the Jamuna, as opposed to completely denying entry of river water and sediment to the floodplain. Hence, all the existing embankments have regulators, sluice gates, or bridges that can pass sediment-laden water into the floodplain, as well as to natural flow points at the distributary offtakes. Such is the case at site 58 on the Older Jamuna floodplain, where ^{137}Cs data evidences some sedimentation (1–2 mm/yr), even though the site is landward of the Sharishabari railroad embankment, which has been in place for about 100 years. River water can also pass through embankments when they are breached by bank erosion or in high floods (as occurred in 1987 and 1988).

Sediment deposition rates would be expected to decrease somewhat as distance from the source to deposition point is increased (see Section 5.1.2). Farmer interviews indicate no clear trend of decreasing sedimentation after embankment construction. This can be assumed, however, since the farmers uniformly mentioned a decrease in flood depth in their fields.

Construction of the GIS model did not introduce constraints produced by embankments. This could be included in future models by using known locations of water passage together with the distance function (see Section 5.4). Large floods would remain a separate case: the 1987 flood image indicates that cross-floodplain flow is relatively unconstricted during major floods.

5.1.4 Influence of Major Floods

Radiocesium data provide a sedimentation rate averaged over about 40 years (since the onset of thermonuclear testing). This averages out the relative effects of major floods. Farmer interviews included enquiries about the last major flood in 1988. The data, summarized in Table 5.2, indicate that large floods cause increased sedimentation in all areas. This is particularly significant in the Older Jamuna and Old Brahmaputra floodplains: the ~2 cm received in larger floods is virtually the only sediment input to these areas. Despite the small quantities relative to other areas, soil fertility still may be affected since this material is fine-grained and therefore of high quality.

The farmer interview is perhaps the only means of generating information about large historic floods. As a check on the validity of this information, the average of "1988" and "normal" flooding depth over 40 years should be comparable to the Cs accumulation rates. This is the case, for instance, in the older areas, where both methods yield an average of about 1–2 mm/yr. The rates determined by both methods have been used in setting up the GIS model discussed in Section 5.4.

The 1987 satellite image classification of turbid and rainwater flooding shows the very different flood regime present in high-flood years. The volume of turbid water on the floodplain becomes so large that down-gradient, along-floodplain flow becomes an important means of sediment delivery. In this case, sediment delivery to older floodplain areas by distributaries is hypothetically unimportant, except that offtakes from the Jamuna become major input points for water that spreads out as sheetflow on the floodplain. Sedimentation is more difficult to predict from models based on input volumes, because the system likely is less closed, and much less predictable, in years when there are high floods. That is, a percentage of the turbid water input entering the floodplain re-enters the river farther downstream.

5.2 Sedimentation and Soils

5.2.1 Soil Characteristics

The soil profile descriptions and laboratory data in Appendix II illustrate two important characteristics of the floodplain soils of Bangladesh. One is the general occurrence of finer material in the upper layers overlying a coarser substratum. The other is the rapidity with which raw alluvium changes into soil under the country's prevailing environmental conditions.

Texture profile. All the profiles described show the presence of finer materials near the surface overlying coarser materials at depth. On the Active and Young Jamuna floodplains, this "fining upward" characteristic of individual flood deposits apparently represents the burial of bed-load materials deposited on the active floodplain by finer wash-load materials deposited in quieter water as the floods recede, both on active floodplains and on adjoining stable floodplain land.

A "fining laterally" process is also evident. The profiles from the Older Jamuna floodplain and the Old Brahmaputra floodplain show higher clay contents in the upper layers of basin soils than occur on the younger floodplains. These fine basin materials may include colloidal clay carried a greater distance from the rivers and deposited in deeper, quieter water. They apparently also include reworked soil material that has been washed from adjoining ridge soils into basins during rainfall. On the oldest floodplain land, these finer deposits have accumulated to a considerable depth (see next section).

On the older parts of the Jamuna and Brahmaputra floodplains, these vertical and lateral fining processes are reversed at a certain stage in soil development. Topsoils in these units have lower clay contents than the underlying subsoils (see profiles 12 and 21). This reversal is attributable to a destructive soil process (ferrolysis) discussed below.

Soil profile development. The profile descriptions illustrate the differences between "alluvium" and "soil" described in Chapter 1. In all profiles, the surface layer (Ap horizon) has been disturbed by plowing. Only in profile 19 (Silty Alluvium) does stratified material occur immediately below this layer. In all the other profiles, a so-called B horizon has formed: i.e., a layer in which soil-forming processes have altered the original physical and chemical properties of the parent material. The underlying stratified alluvium is designated C horizon.

These changes in the B horizon are indicated by such properties as: absence of alluvial stratification; prismatic and/or blocky structure instead of the original stratified, platy structure; yellow or brown oxidation mottles; and, in some profiles, the presence of coatings on the faces of subsoil pores and structural units. These soil changes have occurred to a depth of 30 cm in profile 3 on the active floodplain, to 56 cm and 80 cm, respectively, in the two profiles from the Young Jamuna floodplain (2 and 16), and to 77 cm and 116 cm in the profiles from basin sites on the Older Jamuna and Old Brahmaputra floodplains (12 and Ghatail Series).

Soils on the Active and Young Jamuna floodplains are near-neutral in reaction in all layers and have relatively low organic matter contents. Soils on the Older Jamuna and Old Brahmaputra floodplains have moderately to strongly acid topsoils, indicating that contributions of neutral-to-alkaline river sediments must be negligible. These older soils also

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have more organic matter in their topsoils than is present in young soils. The thickness of clay material and the depth of acidification and organic matter accumulation in these profiles suggest that they have received fine material washed out of "old" topsoils on adjoining higher land. The fact that radiocesium is confined to the cultivated topsoil layer of these older soils indicates that the rate of accumulation of materials by lateral flow into basin sites must be very slow (<2-3 mm/yr).

The two profiles from basin sites on the Older Jamuna and Old Brahmaputra floodplains have less clay in their surface layer than in the subsoil. This phenomenon is attributable to clay destruction in the topsoil under conditions of seasonally alternating reduction and oxidation sustained over a long period (see Appendix I). On older floodplain land, this process apparently proceeds more quickly than clay sediment deposition, whether such clay is derived from rivers or from lateral wash.

Soil age. The soil profile characteristics described above, together with the evidence from the cesium and sediment collection studies described in Chapter 4, indicate that the deposition of sediments from river water occurs to a significant extent only in a narrow belt on active and young river floodplains (and, presumably, on narrow strips of such land along distributary river channels crossing older floodplains). The greater part of the Jamuna and Old Brahmaputra floodplains apparently has not received significant amounts of new sediment during the past 40 years, except during major river floods (especially in 1974 and 1988).

It seems probable, on the evidence of soil profile characteristics, that the Old Brahmaputra floodplain in the study area has not received a regular input of sediment since the Brahmaputra River shifted to its Jamuna course about two centuries ago. In view of the distance between these areas and the Old Brahmaputra channel, it is also probable that they did not receive new river sediments for several centuries before that time. The most significant sedimentation process on older floodplain land apparently is the redistribution of finer materials from higher land towards lower land, which is attributable to surface runoff when the ridge soils are exposed to heavy rainfall. The additions of sediment received in occasional high floods are comparatively small and insufficient to offset the process of clay destruction in these soils.

Indicators of recent sedimentation. The findings described above indicate that topsoil reaction is the most consistent parameter that could be used to indicate whether or not floodplain soils are receiving significant amounts of new river alluvium. Soils in the study area that do receive regular increments of new sediment, or that have done so within the recent past (possibly <100 years), are near-neutral to alkaline in reaction in all layers. Older soils, which are not receiving significant amounts of new alluvium, have a lower pH in the topsoil than in subsoil layers.

Taking into account information from other floodplain areas of Bangladesh, the important distinction lies in the difference between topsoil and subsoil reaction rather than in the absolute reaction value. On the Ganges floodplain, for instance, where new alluvium is calcareous and has pH values around 8.0-8.4, topsoils remain neutral to alkaline in reaction until some time after the lime has been leached. On this floodplain, therefore, the partial or total loss of lime from the topsoil relative to the subsoil can be used as an indicator that sedimentation has become insignificant. (An exception to this characteristic is known to occur in some ridge soils on old parts of the Ganges floodplain, where soil mixing by ants and other soil fauna constantly brings calcareous material to the surface from lower layers. However, these soils are rarely if ever flooded, and adjoining lower soils that are seasonally flooded have neutral or acid topsoils overlying alkaline and calcareous lower layers.)

Soil color is not a wholly reliable indicator of soil age. Although young floodplain soils generally have paler gray topsoils and lower organic matter contents than old floodplain soils on equivalent topographical sites, exceptions are known to occur. For example, some Young Jamuna floodplain soils can appear dark gray when wet or moist (though they become mid-gray when dry); and some Old Brahmaputra floodplain ridge soils lack dark gray topsoils and have lower organic matter contents than some depression soils on the Jamuna floodplains. In general, however, the combination of dark gray color and strong acidity in topsoils is a good indicator that they are old and unaffected by recent additions of river sediment (though an exception to this occurs in some tidal floodplain areas where acid sulphate soils occur); and the color of subsoil coatings (gray in young soils; and dark gray in old soils) is another good indicator.

5.2.2 Soil Fertility

The contribution of new river sediments to soil fertility can be approached in two ways: by a nutrient-balance method that compares the quantity of nutrients added in sediment with the quantity of nutrients extracted by crops growing on the site; and by comparing the nutrient status of soils at different distances from the river source and that, on the basis of this study, probably receive different amounts of sediments.

Nutrients in sediments. Table 5.3 shows the assumed levels of nutrient offtake by crops grown in the two study blocks, as described in Section 3.1.9. The balance between nutrients added in sediments and fertilizers and the assumed offtake by crops, for six sites where sediment samples were collected in 1994, was calculated and presented in Table 5.4. For comparison, data are included for two sites where no sediment was deposited. Tables IV.1a and IV.1b in Appendix IV show the physical characteristics of the sampling sites and crops grown on them.

At the sites receiving sediment, the figures in Table 5.4 imply positive nutrient balances for nitrogen, phosphorus, and sulphur and a negative balances for potassium at all except site 24, where 30 cm of sediment were deposited in 1994. However, the implications of this exercise and the figures shown in Table 5.4 are at best indicative and should be treated with extreme caution for a number of reasons.

Table 5.3 Assumed Levels of Nutrient Uptake by Crops

Crop	Yield T/ha	Nutrient Uptake T/ha
SHARISHABARI		
Boro (HYV)	5.9	0.267
Wheat	2.8	0.193
T. Aman (L)	2.3	0.110
Jute	2.2	0.223
Millet (kaon)	0.8	0.850
Mustard	1.1	0.790
Sesamum	0.5	0.570
KALIHATI		
Mixed Aus & Aman	2.8	0.140
B. Aus	2.2	0.102
Wheat	2.2	0.151
Jute	2.5	0.251
T. Aman (L)	2.4	0.143
Boro (HYV)	5.9	0.269
Mustard	1.4	0.100
B. Aus	2.7	0.136
Black gram	1.3	0.089

Source: BARC (see Section 3.1.9)

(a) Only one site (24) recorded a significant amount of sediment.

(b) Correlations between nutrient levels determined by laboratory analysis and crop performance or response to fertilizer applications in the field usually are weak or non-existent.

(c) Sediments deposited in 1994 were on flooded lands and subject to considerable chemical changes between their aerated and submerged conditions, as was described in Chapter 2.

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Table 5.4 Relative Contributions of River Sediment Deposits to Soil Nutrient Status

Sample No.	Source	Sediment Thickness (cm)	Nutrients (kg/ha) N	P	K	S
21	Sediment	0	0	0	0	0
	Fertilizer		-40	41	31	0
	Crop off-take		144	34	184	22
	Balance		-104	+7	-153	-22
24	Sediment	30	869	401	130	1270
	Fertilizer		24	0	0	0
	Crop off-take		92	20	126	13
	Balance		+801	+381	+4	+1257
25	Sediment	0.02	782	98	61	186
	Fertilizer		42	0	0	0
	Crop off-take		135	33	207	18
	Balance		+689	+65	-146	+168
26	Sediment	0.01	693	93	65	293
	Fertilizer		66	27	12	4
	Crop off-take		134	24	178	19
	Balance		+625	+96	-101	+278
7	Sediment	Trace	194	73	12	119
	Fertilizer		42	24	4	0
	Crop off-take		137	22	116	16
	Balance		+99	+75	-100	+103
8	Sediment	Trace	552	138	60	253
	Fertilizer		78	15	8	2
	Crop off-take		169	42	256	24
	Balance		+461	+111	-188	+231
12	Sediment	0	0	0	0	0
	Fertilizer		66	26	19	0
	Crop off-take		143	25	182	20
	Balance		-77	+1	-163	-20
3	Sediment	Trace	304	58	21	312
	Fertilizer		57	18	4	0
	Crop off-take		169	25	182	20
	Balance		+192	+51	-157	+292

(d) If sediments were providing the large amounts of nitrogen and phosphorus indicated, farmers would not need to apply fertilizers at these sites.

(e) The large negative balances for potassium and large positive balances for sulphur appear contrary to research findings and to farmers' experience. Potassium fertilizer requirements are rarely found to be more than a fraction of the levels suggested by the "deficiencies" indicated. On the other hand, sulphur has been found to be deficient over large parts of the country.

(f) The nutrient contents in the sediment samples seem to bear little relation to the nutrient levels measured in topsoil samples taken from the same sites. Table 5.5 compares nutrient levels in sediment and topsoil samples from six of the sites included in Table 5.3. The much higher levels of organic matter, nitrogen, and sulphur in some sediment samples than in adjoining topsoils could possibly be due to differences in the proportion of the total sample that algal residues on the surface contributed to the very thin sediment deposits relative to topsoil samples 10 cm thick. This possibility deserves investigation in future studies of this kind.

This finding is discussed further in Section 6.3.

Soil nutrient status. Comparison of the laboratory data for the soil profiles from different physiographic units indicates that soil nutrient status is not directly linked with sedimentation. Soils on the

Table 5.5 Comparison Between Selected Nutrient Levels in Sediment Samples and Adjoining Topsoil Samples

			Nutrient						
			OM	Ca	Mg	K	NH⁴	P	S
Site No.	Source	pH	%	meq/100 gm			µg/ml		
24	Sediment	6.9	0.2	4.2	1.3	0.1	13	6	19
	Topsoil	6.3	0.4	0.4	0.3	0.0	13	7	17
25	Sediment	6.9	4.6	7.9	1.9	0.3	162	17	45
	Topsoil	6.8	0.4	4.6	0.8	0.1	27	15	10
26	Sediment	7.0	5.2	7.9	1.9	0.5	187	21	89
	Topsoil	6.9	0.4	5.0	1.6	0.1	33	11	20
7	Sediment	7.4	4.5	7.9	1.7	0.3	173	65	106
	Topsoil	7.1	0.9	7.1	2.1	0.1	27	8	12
8	Sediment	6.8	0.9	7.6	2.2	0.2	72	18	33
	Topsoil	6.8	1.0	8.0	3.4	0.1	31	16	2
3	Sediment	7.3	3.8	6.5	1.6	0.2	115	22	118
	Topsoil	7.2	0.8	7.0	2.3	0.1	58	15	2

Note: Sediment samples were from cloth (site 24) and the average of cloth and mat (sites 25 & 26). Sediment samples for sites 7, 8, and 3 were from traps.

Active and Young Jamuna floodplains, which have received recent increments of new alluvium, do not have higher nutrient contents than soils on the older floodplains that apparently have not received such sediments. In fact, contents of important plant nutrients such as calcium, magnesium, nitrogen, phosphorus, and sulphur in the topsoils of the active floodplain soils, which receive most sediment, are lower than those in the older soils, which receive little or none. Similarly, young, unleached soils do not necessarily have higher nutrient contents than older soils with acid topsoils.

The higher nutrient status of soils on the older floodplains probably is linked to their higher contents of clay and/or organic matter: more nitrogen and sulphur with higher organic matter contents; more exchangeable cations with higher clay and organic matter contents. The higher iron and manganese levels in profile 12 probably reflect both the high content of organic matter and the acidity in this soil.

The possible contributions of blue-green algae (BGA) to floodplain soil fertility were not assessed by this study. As was discussed in Chapter 1, BGA activity probably is greater in clear water than in silty water. In the study area, therefore, the contribution of nitrogen by BGA probably is greater in older floodplain areas flooded by clear water than it is in Active and Young Jamuna floodplain areas where floodwater is clouded by silt.

Moderately and deeply flooded land on stable floodplain areas also has more vegetation—both crops and weeds (including aquatic weeds)—than active floodplain land. This provides more residues, which in turn provide more soil organic matter. Over time, this builds up to an equilibrium level for the local environment: least on active floodplains; more on young floodplains (and more in depressions than on ridges); most in old floodplain basins. The highest amounts of organic matter are found in some perennially wet old floodplain basins outside the study area. Peaty topsoils occur in parts of the Sylhet Basin; and thick peat and muck deposits are found in the Gopalganj-Khulna *Beels*. These peaty materials, it may be noted, are not rich in nutrients and are potentially strongly acid if drained and oxidized. Their occurrence indicates that the amounts of river sediments reaching such basins is very small indeed.

5.3 Sediment Balance Estimates

This study estimated overall floodplain sedimentation based on sediment transport measurements made by the Bangladesh Water Development Board (Appendix V). This was done by defining a fluvial system comprising the three major rivers, the Jamuna, Ganges, and Padma (see Figure V.1, Appendix V). The system also includes the Dhaleswari and Gorai rivers, which are distributaries of the Jamuna and the Ganges, respectively. The inflow boundaries of the system are at Bahadurabad on the Jamuna River and at Hardinge Bridge on the Ganges. The outflow boundaries are at Baruria on the Padma, at Kushtia on the Gorai River and at Jagir and Taraghat on the Dhaleswari. The sediment transport data cover the period 1966–1992 (details of data quality and data analysis methods are described in Appendix V). Due to the difficulty of gauging sedimentation in such a vast river network, the limited resources deployed to do so, and the significant amount of missing information, the estimates presented must be considered very general and indicative. Despite such limitations, data from different periods are consistent.

Mean annual sediment transport estimates through the Jamuna River at Bahadurabad range from 387 million tons (MPO 1987) to 650 million tons (Hossain 1992). In the Ganges River at Hardinge Bridge, the estimates range from 196 million tons (CBJET 1991) to 549 million tons (RSP 1994). The export estimates out of the system range from 563 million tons (MPO 1987) to 894 million tons (RSP 1994). These estimates cover the entire amount of suspended sediment transport from clay to sand. Figure V.7 (Appendix V), which shows the sediment balance based on different size fractions, indicates that about 6 million tons of sand remains within the fluvial system; the silt-clay fraction

Table 5.6 **GIS Model Estimates of Sediment Deposition with Distance From Sources**

	Distance				
	0–0.1	0.1–0.2	0.2–0.5	> 0.5	Total
Sediment, metric tons (% of total)	14,918,044 (51)	5,994,269 (21)	3,637,459 (12)	4,714,464 (16)	29,264,236
Area, ha (% of total)	16,135 (7)	20,504 (9)	31,876 (14)	164,922 (70)	233,437
Tons/ha	925	292	114	29	–
Deposition Thickness (cm)	6.17	1.95	0.76	0.19	–

remaining within the system is about 169 million tons. Together, these figures represent about 15 percent of the total sediment input. This amount remaining within the fluvial system can be translated into overall sedimentation rates in the floodplain. An estimate based on GIS mapping and analysis by FAP 19 indicates that an area of 6,500 km^2 to 10,148 km^2 is annually inundated, according to two boundary determination methods. The sequestered amount of sediment therefore accounts for an annual average sedimentation rate of from 7.5 to 11.5 mm/yr. It is recognized that there is a great degree of spatial and temporal variability in the sedimentation process.

5.4 GIS Modelling of Floodplain Sedimentation

Riverine sediments are primarily deposited by two distinct processes—lateral deposition from migration of the river channel, and vertical accretion from overbank flooding (see Section 1.2.1). It is the latter mechanism that this study sought to model.

The floodplain itself can be divided into two distinct active sedimentation zones identified by their depositional mechanisms and their proximity to sediment sources: the natural levee and floodplain/backswamp. A natural levee is formed when floodwaters spill over a riverbank and deposit a higher proportion of relatively coarse sediments, creating a splayed landform adjacent to the riverbank. According to Allen (1970), the width of levees ranges from one-half to four times the channel width, and their elevation is between a few decimeters to as much as 8 meters, depending on river size and sediment load. This landform usually is higher in elevation than adjacent floodplain/backswamp areas, which are characterized by low flow velocities and are seasonally drained. In these areas, vertical accretion deposits mostly fine sediments. The processes in these two zones have been simulated in the GIS model using a distance function for the natural levees and physiography-based minimum annual deposition rates for floodplain/backswamp areas.

The deposition rate predicted by the model is very high immediately adjacent to the source of sediment, as dictated by the distance function, and then drops off rapidly. The high rates adjacent to the river in the model simulate deposits of coarser sediments that are rapidly deposited as natural levees. The slower depostion of finer sediments throughout the period of inundation is represented by the threshold rates associated with different physiography. The GIS sedimentation model output shown in Figure 4.6 displays linear bands of decreasing sedimentation rate categories that parallel the river channels, simulating this process. The high sedimentation rates adjacent to the sources are responsible for the bulk of the sediment, which is deposited in a small proportion of the total area within the natural levee zone (Figure 4.7). Table 5.6 shows the GIS model estimates of total annual sediment deposits for various distances from the sediment source. About half of the total

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sediment is deposited in a relatively small area within 100 meters of the sources and 84 percent is deposited within 500 meters of the sources. The remaining 16 percent of the sediment is distributed over some 70 percent of the floodplain area.

5.4.1 Comparison of GIS Model Results with Sediment Balance Estimates

The sediment budget for the Jamuna-Ganges-Padma river system is examined in detail in Appendix V. The assessment, based on CBJET and River Survey Project data, estimates that some 76 million m^3 of coarse sediments and 117 million m^3 of fine suspended sediments are unaccounted for in the river system and presumably deposited annually on the associated floodplains or riverbeds. The floodplain area associated with this fluvial system, as derived from GIS analyses of data on physiographic units, river catchment boundaries, and topographical and infrastructural information, was estimated to be some 10,148 km^2. This translates to average depths of 7.5 and 11.5 mm/yr (Table V.2, Appendix V). These values compare favorably with the 7.6 mm/yr predicted by the GIS model for the study area of this project, which encompasses a generally representative area of some 2,554 km^2 within the larger fluvial system.

5.4.2 Comparison of GIS Model Results with Field Data

In this section, GIS modelling results are compared with field data collected as part of this project, including data compiled from sediment collection devices, and sedimentation rates as reported by farmers and the ^{137}Cs analysis results. The field data were not collected systematically, and each data point represents conditions at isolated points on the floodplain; it is therefore likely that averages from these data are not representative. The GIS model results, on the other hand, summarize all conditions, including relatively high depositional areas adjacent to sediment sources and areas receiving relatively low amounts of sediment such as floodplain backswamps.

Comparison of the mean annual sediment depth generated by the GIS model with the data compiled from sediment collection devices in the field is difficult because the relatively dry monsoon season of 1994 failed to inundate most of the sediment sampling sites. Regardless, some sample sites in both study blocks yielded sediment data. The bulk of these registered a sediment depth of 2 mm or less. This is consistent with results of the GIS model for areas 0.8 km or more from sediment sources, which was the case for most of the samples. The main exception was a sample within 100 meters of a river that received a total of 30 cm of sediment during the monsoon season, consisting mostly of coarse fractions.

Averages of mean sedimentation rates reported by farmers at the field sampling sites (Table 5.7) disagree with the GIS model results (Table 4.6) for the various physiographic units. The average value reported by farmers for the Active Jamuna sites was 14 cm/yr, which is more than an order of magnitude greater than the 1.15 cm/yr pre-

Table 5.7 Estimated Annual Sedimentation Rates (cm)

Floodplain Region	GIS Model	Farmer Reports	^{137}Cs Analysis
Active Jamuna	1.15	14	1.32
Young Jamuna	0.81	2.1	1.24
Old Jamuna	0.71	0.1	0.29
Old Brahmaputra	0.67	0	0.15

dicted by the model for this physiographic unit. The 2.1 cm/yr value for the Young Jamuna floodplain is also more than twice that predicted by the GIS model (0.81 cm/yr). The Older Jamuna floodplain is reported to receive 0.1 cm/yr of sediment, which is well below the GIS model prediction (0.71 cm/yr). However, farmers reported an absence of sediment deposition in the Old Brahmaputra floodplain, again short of the GIS model prediction (0.67 cm/yr). Altough this report is based on only three surveys, their report of no sediment deposition is consistent with the 1 mm/yr rate assumed by the model for areas distant from the sediment sources (> 1.5 km). This conclusion is based on the assumption that a 1 mm accumulation might go unnoticed by farmers.

Although the GIS model is based partly on results of Cs analysis, it is nevertheless useful to compare gross results of the two methods. Average sedimentation rates from Cs analysis of field samples (Table 5.1) shows Active and Young Jamuna floodplain sample sites were 1.32 and 1.24 cm/yr, compared with 1.15 and 0.81 cm/yr from the GIS model (Table 4.6). The Old Jamuna and Old Brahmaputra floodplain average values differ significantly: 0.29 and 0.15 for the Cs analysis, and 0.71 and 0.67 cm/yr for the GIS model, respectivley. One might expect more agreement since the GIS model is based on a source-distance function derived from the Cs samples (Figure 3.15). However, the function is not based on a proportionate amount of samples from each physiographic unit, and only the Young Jamuna samples are evenly distributed about the curve. This suggests the need for a more extensive and systematic field sampling strategy to refine the source-distance function used in the model; an increase in the number of Cs samples, and an even distribution with respect to physiographic unit and distance, would yield a more finely calibrated function. Stratification of results based on floodplain geomorphic features such as levee zones versus backswamps, in addition to physiographic units, also would produce more appropriate comparisons.

5.5 Synthesis of Results

The findings of this study provide important new information on the rate and location of sedimentation on the Jamuna floodplain. This has allowed the construction and testing of a first approximation of a floodplain sedimentation model, as described in Section 3.4. Two matters remain to be discussed: to what extent can the model be applied to other floodplain regions of the country? and what lessons were learned that can be used to improve the design of future studies? These questions are addressed below under three headings: sedimentation, soil fertility, and techniques. Chapter 6 presents the recommendations arising from this assessment.

5.5.1 Sedimentation

The findings show that in the study area:

(a) Most sediment is deposited close to the active river channels and amounts decrease progressively with distance from those channels.

(b) Average rates of sediment deposition correlate with the geomorphic ages of floodplain identified by earlier soil surveys. In general, the greater the floodplain age, the lesser the amount of new sedimentation.

(c) Sedimentation rates are not uniform within these physiographic units. Measured average rates were lower in the Sharishabari block than in the downstream Kalihati block. Within each block, considerable local variations occur in the amounts deposited because of the irregular occurrence of distributary channels and spill deposits.

(d) Although there has been a flood embankment on the Jamuna left bank alongside the study area for varying periods up to about 25 years, river sediment continues to enter the floodplain in high-flood years. This happens when the embankment is breached (mainly upstream of the study area), along *khals* linking floodplain basins with distributary rivers, and possibly at times when regulators or sluices in the embankment are opened at farmers' request to let water onto the land during the flood season.

The extent to which these findings can be extrapolated to other areas is discussed below: first for the study area; then for other parts of the Jamuna floodplain; and finally for the country's floodplain area as a whole.

Study area. Sampling was not done on a statistical basis. Because the study was exploratory in nature, a disproportionate number of samples was taken from sites on Young and Older Jamuna floodplains where recent spill deposits were visible in the landscape. Fewer samples were taken from the Active Jamuna and Old Brahmaputra floodplains.

For these reasons, average sedimentation rates may have been overestimated for some physiographic units and underestimated for others. The fact that 1994 was an exceptionally low flood year in the Jamuna and that it was impossible to obtain deep core samples (see Section 3.1.4) may have contributed to an underestimation of active floodplain sedimentation rates. Moreover, the techniques used did not permit making a distinction between sediment derived directly from river floods and sediment washed into depressions by local runoff. Recommendations regarding interpretation of the study area findings are made in Section 6.3.

Jamuna floodplain. The proportions of the four physiographic units in the study area—Active, Young, and Older Jamuna floodplain, and Old Brahmaputra floodplain—change from north to south across the area. As Figure 3.10 illustrates, in east-west cross-sections between the Jamuna River and the Madhupur Tract, the proportion of Young Jamuna floodplain land increases southward at the expense of Active and Older Jamuna floodplain, and Old Brahmaputra floodplain. On the remainder of the floodplain south of the study area, the proportion of Young Jamuna floodplain increases further and the Old Brahmaputra floodplain disappears.

Extrapolating the study area findings to the southern half of the Jamuna floodplain is difficult because there are important differences between the two parts of the floodplain. In the first place, the Older Jamuna floodplain was not specifically recognized in the Dhaka district soil survey (SRDI 1967c). However, the survey did consider an area of slightly calcareous soils near Manikganj to have developed in mixed Atrai, Ganges, and pre-Jamuna sediments deposited before the Jamuna invaded the region. Some "windows" of old basin clays mapped within the Jamuna floodplain east of Manikganj were also identified as pre-Jamuna deposits.

Second, the northern and southern parts differ in river and flooding characteristics. The Jamuna floodplain is much wider in the south than it is in the study area, there is a greater proportion of deeply flooded land, and the rivers are mainly unembanked. Flooding directly from the Jamuna apparently is much less important than flooding from the Dhaleswari-Kaliganga distributary (and distributaries of that river) and by runoff from the Older Jamuna and Old Brahmaputra floodplains to the north (which probably comprises varying proportions of river water and rainwater from year to year according to differences in rainfall, Jamuna river levels, and whether Jamuna embankments are breached or not). River levels and overland flow in this area can also be influenced by adjoining or downstream water levels at the Ganges-Jamuna confluence, in Arial *Beel,* and in the Padma and Lower Meghna rivers, which can vary independently of levels in the Jamuna.

A third difference is in river dynamics. The Dhaleswari only shifted into its present Kaliganga channel in 1941. Since that time, the old channel has almost silted up. Even the Dhaleswari-Kaliganga channel itself has silted up considerably within the past 30 years, as is indicated by river discharge readings. Rivers in the north appear to have retained more stable courses in recent times, although all of them (including the northern intake of the Dhaleswari) appear to have silted up significantly in the past 30 years.

Recommendations regarding the extrapolation of study area findings to the Jamuna floodplain as a whole are given in Section 6.3.

Other floodplains. Each of the 23 floodplain physiographic units shown in Figure 2.1 has its own flooding and sedimentation characteristics (FAO 1988, Brammer 1995a). The Jamuna floodplain differs from other floodplains in a number of respects.

(a) Jamuna River discharge and sediment contents are significantly greater than in the Ganges and in the Meghna upstream of its confluence with the Padma.

(b) Almost the entire overland spill from the Jamuna is on one side (the left bank). On the river's right bank, overland flow either is towards the river, on the Teesta floodplain, or is parallel to it, on the Karatoya-Bangali floodplain. (However, this situation could change in the future if the Jamuna were to make its threatened breakthrough into the Bangali channel.)

(c) The Jamuna floodplain is in a highly dynamic state. Since the Brahmaputra moved into its Jamuna channel about 200 years ago, Jhenai and Jamuna sediments have progressively buried an older landscape, a process that apparently continues in the southern half of the Jamuna floodplain. (This infilling applies mainly to the Active and Young Jamuna floodplains. The Old Brahmaputra floodplain, and probably the Older Jamuna floodplain as well, predate the shift in the Brahmaputra course.)

    Only the extreme eastern part of the Ganges river floodplain, where the Ganges River shifted from its former Arial Khan channel into its present Padma channel about 150 years ago, appears to be as dynamic as the Active and Young Jamuna floodplains.

    Although the Teesta shifted from the Atrai into its present channel about the same time as the Brahmaputra shifted into its Jamuna channel, soil surveys on the Teesta floodplain do not indicate a similar proportion of active and young floodplain land to that existing on the Jamuna floodplain. However, the situation on this floodplain is complicated by the large-scale liquefaction and ejection of sediments that occurred in its eastern part in the 1897 earthquake (Khan 1977).

    Rivers and floodplain areas elsewhere in the country apparently have been stable for several centuries.

(d) Flood regimes are significantly different between young river floodplains (such as that of the Jamuna), old river floodplains (such as that of the Old Brahmaputra and most of the Ganges floodplain), piedmont plains at the foot of hills, the old Meghna estuarine floodplain, the young Meghna estuarine floodplain, and the Ganges tidal floodplain. Significant differences also occur within these broad units.

(e) Brahmaputra-Jamuna River sediments have higher mica content than those of Meghna tributaries, and they have much lower montmorillonite clay contents than Ganges sediments. These mineralogical differences may introduce significant differences in the suspended sediment loads of these rivers and the extent to which sediments are dispersed over adjoining floodplains.

(f) Floodplain regions differ in the dates when flood embankments were constructed and the extent to which the embankments (and other infrastructure) have interfered with natural flooding and sedimentation.

These differences make it difficult to extrapolate the study findings beyond the Jamuna floodplain, except in a broad sense. Section 6.3 makes recommendations for conducting field studies on other floodplains.

5.5.2 Soil Fertility

The study findings regarding the supposed nutritional benefits of river sediments show that, in the study area:

(a) Most Jamuna floodplain areas, including parts of the active floodplain, received no measurable sediment deposits during the exceptionally low 1994 flood.

(b) Many parts of the Older Jamuna and Old Brahmaputra floodplains receive river sediment deposits only in years with high river floods, such as in 1988;

(c) The low and intermittent rate of sediment deposition within the mainland part of the study area may (in part at least) be due to the construction of flood embankments on the east bank of the Jamuna within the past 25 years.

(d) The small amount of sediment deposited on all but one of the sampling sites receiving sediments in 1994 may have yielded unrepresentative figures for organic matter and associated nutrient contents, as discussed in Section 5.2.2.

(e) Little relationship apparently exists between nutrient levels determined by laboratory analysis and soil fertility status as indicated by farmers' fertilizer practices.

(f) Soil nutrient levels determined by laboratory analysis generally are lower in young soils, which receive periodic increments of river sediments, than in older soils, which receive little or none.

The extent to which these findings can be extrapolated to other floodplain areas is uncertain. Much of what was presented above about extrapolating the study's sedimentation findings applies equally to the soil fertility findings: i.e., important environmental differences exist between the north and south of the Jamuna floodplain; and physical and hydrological conditions differ between each of Bangladesh's 23 main floodplain physiographic regions (Figure 2.1). Among the important differences between these regions are variations in the mineralogy of river sediments (described in Chapter 1 and Appendix I); and possibly, also, regional and intraregional differences in the contributions to soil fertility made by blue-green algae and by other soil and aquatic flora and fauna (discussed in Chapter 1 and Section 5.2.2).

For these reasons, it would be unsafe to extrapolate the study's findings about the nutrient status of new sediments and soils in the study blocks to other areas without confirmatory studies in those areas or regions. These limitations are in addition to those described in Section 5.2.2 regarding the uncertain relationship between soil nutrient contents determined by laboratory analysis and soil fertility as reflected in plant growth, crop yields, and responses to fertilizer applications. Section 6.3 makes recommendations on this issue for future studies.

5.5.3 Techniques

Because of the lack of previous experience with sampling sediment deposition on the floodplains of Bangladesh, several sampling methods were tried and tested, as described in Section 3.1.4. Unfortunately, the year of testing (1994) was an exceptionally low-flood year and the majority of sites originally selected for sampling were not flooded. Among other things, this meant that it was not possible to compare amounts of sediments deposited on cloths/mats with those collected in traps. This limitation was overcome to some extent by sampling six substitute sites as floodwater spread onto low-lying land in the Kalihati block. Nonetheless, the study gained valuable experience with sampling techniques, which can be used to improve sampling in future studies.

Important lessons learned about sampling techniques from the 1994 study included:

(a) Soil survey reports provide a useful guide to geomorphic units within which sampling sites can be selected, but soil maps may need to be updated in active and young floodplain areas where rapid landform and soil changes have taken place since the time of survey. Changes in flood and flooding characteristics due to the implementation of flood control, drainage, and irrigation projects may also need to be taken into account.

(b) Employing a local person to guard and monitor sampling sites provided adequate security.

(c) Cloths, mats, and traps proved to be satisfactory sediment collection methods, but measuring the thickness of sediment deposited on a marker layer of brick dust did not, at least where the amount of sediment deposited was small.

(d) Laboratory analysis of sediment and soil samples is not a reliable means of determining the nutrient value of sedimentation and flooding.

Chapter 6 makes recommendations to improve the design of future floodplain sedimentation studies.

Chapter 6

RECOMMENDATIONS

6.1 Comparison of Bangladesh's Floodplains with Other Systems

The development and evolution of Bangladesh's floodplains have similarities and differences with other riverine floodplains around the world. The comparisons that can be made are of three types: the nature of the floods, the characteristics of the floodplain, and the nature and magnitude of human alteration to the system.

Nature of floods. Like other river systems with large catchments, the Ganges-Brahmaputra system produces a regular, seasonal flood at a predictable time. With the exception of a few catchment basins having two wet seasons (e.g., the Congo River), all such systems have a single annual flood. Such regular floodplain inundation simplifies modelling. Small river systems, particularly those draining high mountain areas, are characterized by irregular, catastrophic floods that may cause rapid deposition of coarse material or denudation of the floodplain surface (Nanson 1986). In Bangladesh, rising floodwater inundates the floodplain at the same time (June–September monsoon season) that local precipitation is flooding low areas of the floodplain with rainwater. This is characteristic of all South Asian rivers influenced by the southwest monsoon; but in other regions, local seasonal flooding may be absent or occur at other times of the year.

The Ganges-Brahmaputra flooding exhibits another characteristic of major rivers: maximum sediment discharge may precede maximum water discharge by up to 1–2 months (Khan and Barua 1995). This effect has been attributed to offset tributary inputs or time lags related to the storage and depletion of sediment supply stored on channel beds and riverbanks during low-water periods (Meade in prep.). Therefore, sediment concentrations are reduced during the most likely period of overbank transport (maximum flood level).

The character of sediments carried onto the floodplain is strongly overprinted by the individual characteristics of the drainage basin. Both the Ganges and the Brahmaputra-Jamuna originate in high mountain catchments characterized by rapid erosion and physical weathering. Relative to other lowland rivers, the rivers of Bangladesh carry a less chemically altered regime of clays (illites and smectites) onto the floodplain, with greater potential soil fertility. Coupled with that is the rapid breakdown of sediments into soils observed in the Bangladesh climate. This may be counterbalanced, in part, by the granulometry of Ganges-Brahmaputra sediments that decreases the quantity of this high-quality clay. The Brahmaputra-Jamuna, in particular, carries a silt-rich sediment load relative to many other rivers. The high silt-to-clay ratio means the river is relatively deficient in clay minerals, which are the main source of cations for soil fertility.

Nature of floodplains. Sedimentation rates observed by this study are on the same scale as those observed in other systems (see Table 1.2). Unfortunately, little or no quantitative data are available for other South Asian rivers, the most relevant for comparison. In fact, it can be said with some assurance that the results of this study, when combined with 30 years of soil studies in Bangladesh and the GIS information, provide as good a database on floodplain sedimentation as is available for any large river in the world.

The Brahmaputra-Jamuna, and Ganges rivers, and particularly the Jamuna, are distinguishable by extreme rates of lateral migration (up to 800 m/yr for some reaches). This indicates that the average life span of a floodplain area is on the order of centuries before it is recycled by riverbank erosion. This compares with recycling rates of millennia or tens of millennia observed in more stable major rivers like the Amazon or Mississippi (Meade in prep.). This lateral recycling rate is complicated in Bangladesh by a trend of downstream aggradation. Both the Jamuna and the Ganges appear to be infilling the alluvial valley and progressively silting up downstream distributaries. On the Jamuna, the Dhaleswari has been silting up for the past 20–30 years, as distributaries upstream seem to have done earlier. There are remnants of several earlier distributaries on the Ganges floodplain, of which only the Gorai remains open (though it is in decline): the Hoogly is artificially maintained by the Farakka barrage. This progressive movement eastward (Ganges) and southward (Jamuna) is burying older tidal and estuarine sediments. Progressive infilling is characteristic of river systems where there has been a major change in base level, caused by an increase in relative sea level from glacio-eustatic variations or regional subsidence. The relative impact of these two factors in Bangladesh is unknown.

Overbank processes, on the other hand, resemble those observed elsewhere. Many rivers develop natural levees and crevasse splay deposits. Figure 1.2 demonstrates that an exponential decrease in sedimentation rates and grain size also has been observed in other systems. One aspect that is fairly unique is the presence of distributaries, as opposed to the dendritic pattern of tributaries found in most large river systems. These distributaries on the Jamuna and the south bank of the Ganges serve to deliver sediment much farther onto the floodplain than is typical, and also to generate relief in these areas.

Tectonic activity in Bangladesh may play a larger role in sedimentation processes than it does for rivers in more stable regions. Earthquakes, for example, can precipitate avulsions of the major rivers, as occurred in the 1780s, when the Brahmaputra shifted to its current Jamuna channel. Equally important, but less well understood, is the effect of tectonic subsidence and basement uplift. Subsidence may slow the elevation rise of any floodplain area with continued sedimentation, resulting in greater sediment accommodation. In addition, differential regional subsidence may contribute to river channel migration.

Human alteration. The Ganges-Brahmaputra floodplains are intensively settled and farmed, and earlier sections have described the possible effect this has on sedimentation. However, river control is incomplete compared with many river systems. Floods such as occurred 1988 are a reminder of the incomplete control over the flow of water and sediment onto the floodplains. On the Mississippi and Rhine rivers, for example, embankment control has reached a more complete stage. Flood control of the Nile was accomplished in the 1960s by construction of the Aswan High Dam. Both processes have been shown to exact environmental tolls in systems that normally receive significant sediment. In both the Mississippi and the Nile, the deltaic portion of the system is experiencing rapid land loss because subsidence is not counteracted by new sedimentation. The Nile also is experiencing soil fertility loss on the floodplain because sediment input from annual floods has been denied.

Several universal scientific problems relevant to the situation in Bangladesh and needing to be addressed can be identified from existing studies of river sedimentation. These include:

- ***Sediment budgets.*** For few systems is there a thorough understanding of the input and output balances of sediment and water in rivers and the adjacent ocean. Such an understanding would be invaluable for calculating the cycling of various particle-reactive and dissolved nutrients, inorganic and organic compounds, and pollutants.

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- *Large floods.* Existing floodplain sedimentation studies have not compiled a sufficient temporal database to determine the relative effects major floods have on the system.
- *Overbank flow models.* Existing quantitative models of water and sediment transport onto the floodplain are relatively crude compared to models of channel flow and lateral accretion. Several major processes (e.g., down-gradient flow within the floodplain, bed-load transport, the effect of vegetation on bed roughness, etc.) have not been addressed at all.
- *Base-level changes.* What effect does a rising sea level have on sediment transport upstream, including flow onto the floodplain? Does subsidence (tectonic and sediment compaction) play a role in relative sea level rise?
- *Planform changes.* How does the river morphology planform affect overbank flow? Can these processes be modelled?

6.2 River Control, Sedimentation, and Soil Fertility

Two study findings have important implications for floodplain soil fertility. One is that, except in excessive floods, the bulk of river sediments are deposited on narrow strips along active river channels with substantially lesser amounts being deposited in young floodplains; most older floodplain land receive little or no new sediments. The other finding is that the soils receiving significant amounts of new sediment do not appear to have higher nutrient contents than soils where sedimentation is insignificant or absent.

It must be emphasized again that due to the nature of this study, firm conclusions cannot be derived from these findings, however, it is believed that they are clearly supported by the body of data and observations. The findings have an important implication for the planning and operation of flood protection works. Such interventions apparently would deprive only a proportion of protected areas from annual or frequent sediment deposition; the reduction of sediment supply probably would be even less under the concept of controlled flooding that is currently advocated. Therefore, it does not appear that cutting off or reducing sediment supplies *alone* would have a significant negative impact on soil fertility for most areas, at least in the short and medium terms.

If, however, flood control works reduce the depth and duration of seasonal flooding on certain protected lands, then the fertility benefits derived from biological sources could be significantly affected. The earlier studies reported in Chapter 1 indicate that BGA can contribute significantly to the fertility of Bangladesh's floodplain soils, especially on deeply flooded land. This study did not examine the contribution blue-green algae (BGA) and other biological agents make to soil fertility. However, the relatively high contents of organic matter found in several of the sediment samples collected suggests that such organic agents were significant contributors to the nutrient content of the new deposits (see Section 5.2.2 and Table 5.3).

6.3 Future Studies

Because of the significance of the above findings for river control planning, it is recommended that confirmatory studies be carried out on the Jamuna floodplain and be extended to other floodplains where flood protection works are already in place or are planned. The purpose would be to assess the actual impact on soil fertility of different kinds of protection, drainage, and irrigation works. These studies should take into account the different cropping patterns and levels of fertilizer use that follow such interventions, the length of time that the more intensive practices have been used, any interruptions in flood protection that may have occurred due to embankment breaching or excessive rainwater flooding, and the contributions that biological sources make to soil fertility inside and outside protected/drained/irrigated areas.

Benefitting from lessons learned from this study, which were discussed in Section 5.5, it is recommended that the following studies be carried out to confirm, supplement, and extend the present study's findings. Separate recommendations are made for the determination of sedimentation rates, techniques to be used, and assessment of soil fertility benefits.

6.3.1 Sedimentation

Study area. Because of the exceptionally low flood of 1994, it is recommended that the study be continued on the Jamuna floodplain in 1995. The Sharishabari block should be retained, but another block should be selected in place of the Kalihati block, where Jamuna Multipurpose Bridge works are likely to interfere with natural flooding. It is recommended that the new block be in the southern half of the Jamuna floodplain, in Daulatpur *thana* of Manikganj district, between the Jamuna and Dhaleswari channels.

Both this block and the one at Sharishabari should be extended to include active charland within the Jamuna River. Physiographic maps of each block should be prepared on the basis of soil survey maps, and updated in the field in areas near rivers where landform and soil changes may have occurred since their original mapping. Additionally, as recommended in Section 6.3.2, supplementary information should be collected along a section crossing the entire southern part of the Jamuna floodplain.

Old floodplain land. The 1994 study only investigated river sediment contribution to soil fertility on relatively young floodplain land. Because of the low flood levels, no direct measurements were made of the amounts of sediments reaching older floodplain land, which is flooded mainly or entirely by rainwater. Soil analyses show that soils on these older floodplains, especially those in basin sites, often contain greater amounts of clay, organic matter, and important plant nutrients than young floodplain soils. The possible sources of the additional clay—whether from the main river, from interior rivers carrying local runoff, by sheetwash from adjoining ridges, by mineral weathering within the soil, or by a combination of such processes—deserve further investigation; so too do the possible sources of the higher organic matter levels and nutrient contents in such soils.

To this end, it is recommended that the Sharishabari block be extended to include part of the Old Brahmaputra floodplain and that additional sites in old floodplain regions be included in future sedimentation studies. Agricultural research funds should be allocated to determine the sources and processes of nutrient supply in old basin soils, possibly including the use of radioactive tracer techniques.

6.3.2 Techniques

It is recommended that the following changes be made in designing and carrying out future floodplain sedimentation studies.

Sampling points. To obtain a better basis for statistical analysis, it is recommended that sampling points within study blocks be at regular intervals along transects crossing the floodplain perpendicular to the alignment of the main Jamuna River channel. The preferred method would be to use a grid of transects, which might allow researchers to obtain a picture of variations within each block.

Sampling techniques. It is recommended that, as in 1994, cloths or mats, and traps be used to collect sediment samples at all sites within each block, and that the same security measures be used. The amount of sediment collected on cloths or mats should be compared with the amount in sediment traps to assess the relative suitability of these techniques. Vibracore samples should be taken at selected intervals along one or more transects in the Daulatpur block for application of the ^{137}Cs technique.

In addition, it is recommended that observations be made in cropped or vegetated fields surrounding sampling sites. The purpose of this would be to ascertain whether more sediment is deposited on land where vegetation impedes floodwater flow than on sampling sites left bare. Brick dust or some other material should be considered for use in cropped fields as a marker horizon. Above this horizon the thickness of any sediment deposited could then be measured and compared with amounts deposited on neighboring cloths. However, this technique would only be suitable in fields undisturbed by harvesting or plowing during the flood period.

To supplement direct measurements of sediment deposition, it is recommended that, as in 1994, informal farmer interviews be used to collect information on the amount of sediment deposited in "normal" flood years and in 1988. This information should be gathered from both study blocks and along a transect crossing the floodplain alongside the Dhaka-Aricha road between Nayarhat on the Bansi River in the east and the Kaliganga channel near Manikganj in the west. Interview points on this cross-section should be selected at upper, middle, and low points of each successive ridge-and-basin landform. Vibracore samples for Cs analysis should be taken at several points alongside the Dhaka-Aricha road to serve as a control on the information collected from farmers.

If the study of soil fertility aspects of sedimentation is to continue, topsoil samples should be collected at all sampling sites and at farmer-interview points along the Dhaka-Aricha road. These samples should be sent to a laboratory for the determinations indicated in the next section.

6.3.3 Soil Fertility

The poor correlation this study found between soil nutrient contents determined in the laboratory and apparent nutrient use by plants (see Section 5.2.2) is not a wholly unexpected finding to soil scientists. Such correlations often are weak or nonexistent, and a great deal of public and farmers' money can be wasted on soil tests of dubious meaning or value. In view of the importance of assessing the kinds, magnitude, and location of possible changes in soil fertility following water control interventions, it is recommended that future studies use the following techniques.

Laboratory analyses. Sediment and topsoil samples should be analyzed by a laboratory to determine particle size (sand, silt, clay), reaction (pH), and contents of organic matter. (As was indicated in Sections 4.1.5 and 5.5.2, it is not considered worthwhile to determine the contents of other nutrients.)

Survey of agronomic trials/demonstration sites. To obtain direct evidence of the impact sedimentation has on soil fertility, it is recommended that the results of agricultural research trials and fertilizer demonstrations in the study area be reviewed and analyzed. All such sites in the parts of Jamalpur, Tangail, Manikganj, and Dhaka districts west of the Madhupur Tract should be used. If this is not feasible, as many sites as possible within and close to the two study blocks should be used. If the sites of trials and demonstrations carried out in past years can be located and classified reliably, the results for, say, the past five years should be analyzed together with those for trials and demonstrations carried out in the current study year.

This analysis should assess whether fertilizer response is different for sites flooded by silty river water than for those flooded by clear rainwater. Direct observations on such sites could also provide valuable information on the effects (positive, neutral, or negative) of the current year's sediment deposits on crop performance.

If arrangements can be made in time for the 1995 study season, SRDI should be commissioned to identify and classify the sites, and BARC commissioned to review and interpret the data. If this is impossible, the FAP 16 soils consultant should be engaged to perform these activities.

Biological activity. It is important that future soil fertility studies assess the contributions that blue-green algae, other algae, mycorrhiza, terrestrial and aquatic plants, and other biological agents make to floodplain soil nutrition. Such studies

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should be carried out under the aegis of BARC, but could perhaps use specialists from university departments, supported as needed by overseas research institutions. Field observations should be made and biological samples taken at the sedimentation sampling sites, and efforts should be made to correlate findings with relevant environmental parameters within physiographic units, including sedimentation rates, soil nutrient data, and local agricultural practices (including fertilizer use).

Research studies. A program of research studies is needed to establish the extent to which soil nutrient levels measured in a laboratory actually indicate plant nutrient deficiencies and fertilizer requirements. Such research is especially needed for seasonally flooded soils, the chemistry of which is quite different from the upland soils for which methods of laboratory and soil-test analysis were developed and calibrated. Countrywide studies also need to establish whether there are significant differences between the fertilizer requirements of soils that receive periodic increments of river sediments and those that do not. These studies should take into account possible differences in crops, yields, and total annual production between such soils in different agro-ecological zones.

In addition, it is recommended that a comprehensive, systematic program of studies be initiated to determine the contributions made by BGA and other biological agents to water and soil fertility in different floodplain environments. The range of environments studied should include old and young floodplain land, non-flooded to deeply flooded land, flood-protected and unprotected areas of different kinds, irrigated and non-irrigated land, and saline and non-saline tidal and estuarine land. Studies are also recommended to identify the sources of clay and organic matter accumulation observed in old floodplain basin soils.

It is recommended that funds be allocated to BARC to organize and supervise such studies.

6.3.4 Recommendations for Refining the GIS Sedimentation Model

The GIS sedimentation model developed for this study represents a basic framework for modeling floodplain sedimentation processes. The primary variables affecting floodplain sediment deposition have been incorporated into the model to simulate sedimentation processes. Further, the study has attempted to develop a source-distance deposition function by using ^{137}Cs data generated by this study. The GIS maps produced by the model have yielded seemingly reasonable estimates of annual rates and long-term depositional patterns as evidenced by their relative agreement with sediment budgets produced in this same study and with those derived from the sediment balance data of the River Survey Project and CBJET (Appendix V). The average depths reported by farmers indicate that the GIS model may be substantially underestimating rates in the Active and Young Jamuna floodplains and overestimating in the Old Jamuna and Brahmaputra floodplains. The basic concept and fundamentals of the GIS model therefore appear sound, but an improved field sampling strategy and statistical analysis based on floodplain geomorphology and physiography could improve it considerably.

Several driving variables have been simplified or omitted from the model, either due to lack of sufficient data or because their inclusion was impractical within the scope of this project. Complex variables such as the sediment load and size of the rivers and *khals*, discharge and flow velocity, terrain effects, and barriers to flooding such as (raised) roads and embankments could be worked into the model to yield more accurate results. In particular, the inclusion of roads and embankments in the model is a refinement that would adjust the unconstrained patterns suggested by this model to match those actually imposed by the landscapes of Bangladesh. Attributes required to make a road/embankment map useful in a GIS model include construction dates, dimensions, and the location of water control structures such as sluice gates and conduits. Moreover, the effects of these structures on sediment fallout would need to be considered. Another variable that could be improved in the model is that of terrain surfaces. The most detailed DEM available in Bangladesh, that produced for the FAP 19 national database, was used for this sedimentation model. However, a higher-resolution DEM would be useful for more accurate modelling of flood extent and depth.

In addition to the incorporation of more complex variables in the GIS model, a more extensive field sampling strategy could be used to refine and verify the source-distance function used in the model. An increase in the number of field samples and observations should yield a more finely calibrated function. Systematic sampling of transects orthogonal to rivers and *khals* at well-distributed sampling sites would also enhance the function. Furthermore, field sample data could be stratified according to river width or discharge to produce a series of distance functions rather than just one for all rivers and *khals*.

Overall, the sedimentation model developed for this study has been a success. Its results appear reasonable and are generally supported by field observation and analyses. It has laid the groundwork for GIS modelling of the floodplain sedimentation processes that occur in Bangladesh, or for other deltaic environments.

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APPENDICES

Appendix I

SOIL DEVELOPMENT PROCESSES ON THE FLOODPLAINS OF BANGLADESH

Reconnaissance soil surveys carried out in the 1960s and 1970s produced considerable new information on soil formation and land use in relation to physiography and geomorphology in Bangladesh. These findings were published in district and subdivision technical reports, and were later consolidated in two comprehensive reports (FAO 1971, 1988). The 1971 report reviewed soil forming processes; a revised edition is currently in the press (Brammer 1995a). The following account is derived mainly from the latter publication. It focuses on processes occurring in floodplain soils.

Parent Materials

Bangladesh is entirely underlain by sedimentary formations. Sediments of Tertiary and Quaternary ages underlie the northern and eastern hills and the uplifted Madhupur and Barind tracts, which respectively occupy 12 and 8 percent of the country. The remaining 80 percent is underlain by recent sediments on different kinds of floodplains: active; meander; piedmont; estuarine; and tidal. The soils of the study area occupy parts of the Active Jamuna floodplain and the Jamuna and Old Brahmaputra meander floodplains (see Figure 2.1).

Active and meander floodplain sediments of the Brahmaputra-Jamuna, Teesta, and Ganges rivers are derived mainly from metamorphic rocks in the Himalayas and are rich in readily weatherable minerals such as biotite and feldspars in the sand fraction. Young and old Meghna estuarine sediments derived from these rivers are also rich in such minerals. On the other hand, piedmont and Meghna river floodplain sediments derived from the northern and eastern hills generally have low contents of readily weatherable sand minerals (Huizing 1971).

Soil Diversity

A wide range of soils is found on Bangladesh's floodplains. Several factors contribute to this diversity: parent material, geomorphology, hydrology and drainage, and age. Soil patterns often are complex, too. Individual floodplain soils rarely occupy large contiguous areas: generally, they grade into their neighbors over lateral distances of 100–200 meters or less. Because of the environmental conditions, soil development often is very rapid, with soil profiles sometimes developing in new alluvium within 25–50 years.

Brahmaputra-Jamuna and Teesta sediments differ from Ganges sediments in being noncalcareous, and from Meghna river sediments in having much higher contents of weatherable minerals. Teesta sediments have higher mica contents than other sediments. All the sediments contain mixtures of kaolinite, illite, and chlorite clay minerals, and Ganges and Lower Meghna sediments contain a proportion of montmorillonite as well. When first deposited, Brahmaputra-Jamuna and Teesta sediments are near-neutral to moderately alkaline in reaction (pH 6.8–8.0); Ganges and young Meghna estuarine sediments are calcareous with pH 8.0–8.4; and sediments derived from eastern hill areas are slightly acid to neutral (pH 6.5–7.0)

Because of the way in which rivers lay down their sediments—coarse sediments near the channel where floodwater flows most rapidly; finer ones away from the channel where floodwater moves more slowly or stagnates—riverbanks (levees) are raised higher than the land behind them. Over time, as rivers change their courses, this leaves behind a floodplain landscape comprising complex patterns of arcuate ridges (the former river levees) and circular or linear depressions (basins, old channels, or interridge depressions). Associated with this relief, relatively coarser (sandy or loamy) materials occur on the ridges which grade laterally into finer materials (heavy silts or clays) in depressions. On most river floodplains, the difference in elevation between ridge tops and adjoining depression centers is 2–3 meters, but it can be up to about

5 meters in the Sylhet Basin. Local elevation differences on tidal and estuarine floodplains generally are about 1 meter.

Soil Formation

After deposition, sediments are subject to soil formation (unless they are quickly eroded by shifting river channels, as can happen on active river floodplains). Close to river channels, sedimentation may dominate over the processes of soil formation, and soil profiles are stratified throughout (i.e., having layers of alluvium with different textures). Farther away from river banks, soil formation generally dominates over sedimentation and soils have well-developed profiles.

In brief, soil formation on the floodplains of Bangladesh involves the following processes. These are illustrated schematically in Figure 2.6.

- Initial 'ripening' of the raw alluvium (i.e., admission of air into the originally saturated material).
- Homogenization (mixing) by soil animals and by plowing of the topsoil, which gradually breaks up the original stratification from the surface downwards.
- Development of prismatic and blocky subsoil structure, except in sandy materials.
- Formation of subsoil coatings and iron-hydroxide mottles.
- Accumulation of organic matter in the topsoil: more in depression soils, which stay wet for several months of the year, than in ridge soils, which are only occasionally flooded; and more in old floodplain soils than in young soils and new alluvium.
- Leaching of cations such as calcium from the topsoil into the floodwater as a result of seasonal changes between reduced (anaerobic) and oxidized (aerated) conditions in the topsoil. Over a period of a few decades, this process eventually makes topsoils acidic during the period when they are not flooded. However, subsoils remain aerated when submerged and are not affected by this process, except in perennially wet depressions.
- Over time (several decades or centuries), accumulation of clay in depression sites, washed from adjoining ridges when heavy rainfall occurs at times when the soils are not flooded.
- Eventually, as a result of continuing acidification, clay destruction in the topsoil, making topsoils on most old floodplain land lighter in texture than the underlying subsoil.
- In cultivated soils, the formation of a compact plowpan below the cultivated topsoil, especially in soils puddled for the cultivation of transplanted paddy (*aman* and *boro*).

In these processes, two factors are particularly important: soil hydrology and age. Because of the ridge-and-depression relief, soils on the highest ridge tops are only occasionally flooded and they remain aerated throughout the year. Downslope, the depth and duration of seasonal flooding gradually increase, and some basin centers stay wet for most or all of the year. The seasonal alternation of flooding and exposure to air has profound chemical effects that cause significant changes in soil properties over time. These effects are described below under relevant topic headings.

Soil Reaction

When soils are submerged for more than about two weeks, the topsoil becomes chemically reduced (i.e., iron changes from the ferric to the ferrous form). This layer is re-oxidized when air re-enters the soil after flooding ends. The seasonal alternation between ferric and ferrous iron displaces cations (such as calcium and magnesium) from the soil material so that, over time, the topsoil becomes acidic in the oxidized condition. Acidification of the topsoil occurs even on the Ganges river floodplain where the original alluvium was calcareous. Subsoils are not subject to this seasonal reduction-oxidation process: either because of air entrapped below the topsoil when the soils are submerged or, in wet basin centers, because they remain reduced (and neutral) throughout the year.

The differentiation between topsoil and subsoil reaction described above can apparently take place within as little as 25 years if the process is not interrupted by the deposition of new sediment on the soil surface. Thus, away from active river channels, most floodplain soils have topsoils that alternate in reaction between acidic when out of water and neutral when submerged, overlying subsoils that stay neutral to moderately alkaline throughout the year. (On the Ganges river floodplain, where the topsoils of young soils are calcareous, the seasonal change in reaction is between neutral when flooded and alkaline when above water.) The cations displaced by the seasonal iron transformation apparently are removed laterally in the floodwater, not leached downward to accumulate in lower soil layers. So, apparently, is lime leached from calcareous topsoils by conversion to soluble calcium bicarbonate under reduced conditions.

Subsoil Properties

When first deposited, river alluvium is saturated with water. On drying out, air enters the material, more quickly in sandy than in silty material. Entry of air in this 'ripening' process causes some ferrous iron to be oxidized to the ferric state, changing the color of ripened alluvium from an initial gray to olive or olive-brown.

The next processes occur more or less simultaneously, but are best considered separately.

- ***Homogenization***. Mixing by soil animals and disturbance by roots start during the ripening process and accelerate its progress. Mixing gradually breaks up the original stratification, but progress can be slow in sandy layers. Animal holes and roots create tubular pores, which are important for soil aeration, water penetration, and drainage.
- ***Structure***. Drying of the upper part of silty alluvium during ripening causes it to shrink. This produces vertical cracks that gradually penetrate deeper into lower layers, except where these are sandy. These cracks form polygonal (prismatic) structural units. In relatively fine silts and clays, these units eventually crack along horizontal or diagonal lines to form blocky structure.
- ***Coatings***. Under conditions of seasonal flooding, dispersed soil material from the surface washes down pores and cracks between structural units, forming shiny gray coatings (gleyans) on their faces.
- ***Mottles***. The continued entry of air into subsurface layers allows stronger oxidation of the material to occur, producing localized patches of stronger brown and yellow colors surrounded by less-oxidized or gray material. This mixture of contrasting colors is known as mottling.

Organic Matter

Decomposition of leaves, stems, and roots of plants growing on the soil produces humus that gradually accumulates in the upper soil layers, mainly in the topsoil. Organic matter contents usually are higher in depression soils than in ridge soils. That is because prolonged seasonal flooding retards the rate at which organic matter decomposes, whereas ridge soils remain aerated for most or all of the year and organic matter breaks down quickly. Generally, too, organic matter contents are higher on older floodplains than on young floodplains. In fact, dark-colored topsoils in combination with brightly oxidized subsoils are properties that often can be used to differentiate between so-called old and young floodplain soils.

Clay Destruction

Eventually, on most floodplains, topsoils become lighter in texture than the underlying subsoils. There is no evidence in Bangladesh's floodplain soils that significant amounts of clay are leached from topsoils into lower layers: the subsoil coatings (gleyans) described above contain silt as well as clay. Rather, it appears that the seasonal reduction-oxidation cycle described above gradually destroys clay in the topsoil in a process termed 'ferrolysis' (Brinkman 1977, Brammer & Brinkman 1977).

This texture contrast is found on relatively older parts of so-called young floodplains as well as on old floodplains. It occurs on the Jamuna and Old Brahmaputra floodplains in the study area. However, it does not occur on the Ganges river floodplain and in some old floodplain basins elsewhere, despite the fact that soils there have strongly or very strongly acid topsoils. Soils in those areas often have as much clay or more in the topsoil as in the underlying subsoil.

The reason why acidification of topsoils takes place without clay destruction on the Ganges river floodplain is not clear. In old floodplain basins, it appears probable that the process is disguised by the simultaneous deposition of clay derived by surface runoff from adjoining ridge soils. Such basin soils (Acid Basin Clays) may have clay contents of about 80 percent to depths of 50–100 cm or more and be very strongly acidic (pH <5.0) throughout, even within the Ganges river floodplain where the original materials were calcareous.

Nonetheless, evidence of clay destruction is often apparent in these old basin soils in the presence of white silt specks in the topsoil and/or white powdery coatings on subsoil structural faces. This suggests that the rate of clay deposition in such sites is very slow. This is confirmed by the fact that the uppermost of three organic layers present in such soils in the lower part of broad valleys in the Madhupur Tract near Dhaka, dated at ca. 1400 years before the present, lies buried by only about 30–50 cm of alluvial clay.

Plowpan

Nearly all the floodplain soils of Bangladesh are cultivated. Cultivation with the traditional plow fairly quickly forms a compact layer at the base of the topsoil, about 10 cm below the soil surface. This layer (the plowpan) usually is about 5 cm thick. It is especially prominent in soils that are deliberately puddled for transplanted paddy cultivation. Deeper plowing by power tillers, which have been introduced in some areas in recent years, appears to have reduced the thickness of previously existing plowpans but not to have destroyed them.

Plowpans form an important marker horizon in soils. The fact that, over wide areas of older floodplain land, they have not been deeply buried indicates that sedimentation rates from river-water flooding on such land must be negligible. In some old floodplain basins, compact topsoils as much as 25 cm thick occur, suggesting that the plowpan in such sites has thickened as sedimentation on the soil surface has occurred, whether by deposition of colloidal material in suspension in floodwater or by lateral wash from adjoining higher land.

Postscript

The features described above are supported by the findings of the present study, namely that new sedimentation from river flooding apparently is significant only on the active floodplain and locally near channels in older floodplain areas. Elsewhere, flooding is mainly by rainwater under which topsoils become acidic, even on the Ganges river floodplain where new alluvium is calcareous. That acidity could not develop if soils were receiving regular increments of new alluvium that is neutral to alkaline in reaction; nor could soils with a prominent plowpan at the base of the topsoil, with well-developed structure, coatings, and oxidation mottles in the subsoil and in which alluvial stratification has disappeared to depths of 50–100 cm or more.

Soil surveys indicate that, ignoring areas occupied by settlements and water, soils with developed profiles occupy about 85 percent of the country's floodplain area (FAO 1988). Raw alluvium and very young soils developed to less than 25 cm depth (i.e., the soils that may be receiving significant amounts of new flood sediments on their surface) occupy only about 15 percent of the floodplain area.

Appendix II

PROFILE DESCRIPTIONS AND ANALYTICAL DATA FOR SELECTED SOIL PROFILES

Soil series	**Silty Jamuna Alluvium**
Location	Longitude 089°47.0274E Latitude 24°44.6031N
Sample site no.	19
Village	Kumaribari, P.S. Kazipur, Sirajganj District
Physiography	Active Jamuna floodplain
Relief and position	Upper part of very gently undulating ridge
Drainage	Poor. Probable flooding depth about 90 cm for 3 months
Land use	Jute–Transplanted aman(L)–wheat

Horizon	Depth (cm)	Description
Ap1	0–12	**Loam;** olive-gray (5Y 5/2 moist) with few fine distinct yellowish-brown (10YR 5/6) mottles; massive; friable moist; slightly sticky, slightly plastic wet; many roots; clear smooth boundary.
C1	12–21	**Loam;** olive-gray (5Y 5/3 moist) with few fine distinct brown (10YR 5/3 moist) mottles; partially finely stratified and weak medium platy structure; fine tubular pores; friable moist; sticky and plastic wet; few roots; gradual smooth boundary.
C2	21–43	**Silt loam;** olive (5Y 5/3 moist); finely stratified and weak medium platy structure; common fine tubular pores; friable moist; sticky and plastic wet; clear smooth boundary.
C3	43–60	**Sandy loam;** olive (5Y 5/3 moist) with few fine distinct brown (10YR 5/3 moist) mottles; stratified; few fine to very fine tubular pores; friable moist; slightly sticky and slightly plastic wet; abrupt smooth boundary.
IIC4	60–80	**Sand;** light olive-gray (5Y 6/2 moist); single grained; loose moist; nonsticky and nonplastic wet; abrupt smooth boundary.
IIC5	80–95	**Sandy loam;** olive (5Y 5/3 moist); stratified; friable moist; slightly sticky and slightly plastic wet; few iron stains; clear smooth boundary.
IIIC6	95–150	**Sandy loam;** gray (5Y 5/3 moist); stratified; friable moist; slightly sticky and slightly plastic wet; few iron stains; clear smooth boundary.

Table II.1 Analytical Data for Profile of Silty Jamuna Alluvium

Site No.	Name of soil series	Depth (cm)	Particle Size (%)			pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
			Sand (US)	Silt (US)	Clay		%	meq/100g			µg/g							
19	Silty Jamuna Alluvium	0–12	53	34	13	7.2	0.6	5.9	0.9	0.16	36	8	10	0.2	2.6	30	11	0.7
		12–21	51	36	13	7.2	0.6	5.9	1.0	0.14	33	14	12	0.5	2.4	26	17	0.7
		21–43	45	52	3	7.4	0.4	5.6	0.7	0.06	59	7	8	0.3	1.5	9	6	0.5
		43–60	63	34	3	7.4	0.2	3.6	0.5	0.06	36	14	18	0.3	1.2	8	6	0.9
		60–80	95	2	3	7.4	0.1	0.5	0.1	0.02	27	7	10	0.6	0.2	3	3	0.5
		80–95	59	30	11	7.5	0.2	2.2	0.5	0.07	33	12	10	0.5	1.4	8	6	1.5
		95–150	77	18	5	7.4	0.2	2.4	0.5	0.08	33	10	16	0.5	2.2	9	11	1.2

Soil series	**Melandaha**
Location	Longitude 089°47.8489E Latitude 24°23.9946N
Sample site no.	3
Village	Sharifabad, P.S. Bhuapur
Physiography	Active Jamuna floodplain
Relief and position	Middle part of very gently undulating ridge
Drainage	Poor. Seasonally flooded up to 110–120 cm for 4–5 months
Land use	Jute–Transplanted aman(L)–wheat

Horizon	**Depth (cm)**	**Description**
Ap	0–8	**Silt loam;** olive (5Y 5/2 moist); massive; common fine tubular pores; firm moist; sticky and plastic wet; common roots; clear smooth boundary.
B21	8–17	**Silt loam;** light olive-brown (2.5Y 5/4 moist) with common fine distinct yellowish-brown (10YR 5/8 moist) mottles; weak medium prismatic breaks into moderate coarse to medium subangular blocky structure; many very fine tubular pores; firm moist; sticky and plastic wet; common roots; clear smooth boundary.
B22	17–30	**Sandy loam;** olive-brown (5Y 5/3 moist) with few fine prominent dark yellowish-brown (10YR 4/4 moist) mottles; weak medium prismatic breaks into weak coarse to medium subangular blocky structure; common fine tubular pores; friable moist; slightly sticky and slightly plastic wet; abrupt smooth boundary.
C1	30–41	**Silt loam;** dark grayish-brown (2.5Y 4/2 moist); stratified; few common tubular pores; very friable moist; slightly sticky and nonplastic wet; abrupt smooth boundary.
C2	41–70	**Sand;** gray (5Y 5/1 moist); stratified; few fine tubular pores; loose moist; nonsticky and nonplastic wet; clear smooth boundary.
C3	70–80	**Sand;** dark grayish-brown (2.5Y 4/2 moist); stratified; common very fine tubular pores; very friable moist; slightly sticky and slightly plastic wet; abrupt smooth boundary.
C4	80–100	**Sand;** gray (5Y 5/1 moist); massive; few fine tubular pores; very friable moist; nonsticky and nonplastic wet; abrupt smooth boundary.
C5	100–152	**Sand;** gray (5Y 5/1 moist); single-grained; nonsticky and nonplastic wet.

Table II.2 Analytical Data for Profile of Melandaha Series

Site No.	Name of soil series	Depth (cm)	Particle Size (%)			pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
			Sand (US)	Silt (US)	Clay		%	meq/100g			µg/g							
3	Melandaha	0-8	29	52	19	7.2	0.8	3.8	1.5	0.10	33	7	8	0.2	2.5	56	15	0.7
		8-17	27	52	21	7.3	1.1	7.0	2.8	0.10	36	7	6	0.3	2.2	37	8	0.8
		17-30	57	30	13	7.3	0.4	5.8	2.3	0.09	33	7	8	0.4	1.4	24	8	0.6
		30-41	93	2	5	7.3	0	1.8	1.2	0.03	17	8	8	0.4	0.2	7	2	0.6
		41-70	94	2	4	7.3	0	0.5	0.5	0.02	7	11	10	0.3	0.1	1	1	0.6
		70-80	68	26	6	7.2	0.4	3.3	1.0	0.05	7	8	10	0.3	1.0	11	5	0.7
		80-100	90	6	4	7.3	0.2	0.5	0.4	0.02	7	8	9	0.4	0.3	2	2	1.0
		100-152	90	6	4	7.3	0	0.5	0.3	0.02	10	8	10	0.4	0.1	3	1	0.7

Soil series	**Sonatola**
Location	Longitude 089°48.7811E Latitude 24°44.4619N
Sample site no.	16
Village	Char Dasherbari, P.S. Sharishabari
Physiography	Young Jamuna floodplain
Relief and position	Upper part of very gently undulating ridge
Drainage	Poor. Seasonally flooded 60–90 cm deep for 4 months
Land use	Transplanted aman(L)–wheat

Horizon	**Depth (cm)**	**Description**
Ap	0–11	**Silt loam;** olive (5Y 5/3 moist); massive, breaks into cloddy structure; common very fine tubular pores; firm moist, slightly sticky and slightly plastic wet; many roots and few shells; gradual smooth boundary.
B21	11–32	**Loam;** olive (5Y 5/3 moist) with few fine prominent yellowish-brown (10YR 5/8 moist) mottles; moderate medium subangular blocky structure; common fine and many very fine tubular pores; firm moist; sticky and plastic wet; nearly continuous thin gray coatings along ped faces; clear smooth boundary.
B22	32–56	**Loam;** olive brown (2.5Y 4/4 moist) with few fine distinct yellowish-brown (10YR 5/8 moist) mottles; moderate medium prismatic breaks into moderate medium to fine subangular blocky structure; many fine tubular pores; firm moist; sticky and plastic wet; nearly continuous gray coatings along ped faces; clear smooth boundary.
B3	56–80	**Loam;** light olive-brown (2.5Y 5/4 moist) with common fine and medium distinct dark yellowish-brown (10YR 4/4 moist) mottles; weak coarse to medium prismatic structure; many fine tubular pores; friable moist; slightly sticky and slightly plastic wet; nearly continuous gray coatings along ped faces; clear smooth boundary.
C1	80–106	**Silt loam;** light olive-brown (2.5Y 5/4 moist); moderate fine to medium platy structure, partially stratified; common fine tubular pores; friable moist; slightly sticky and slightly plastic wet; abrupt smooth boundary.
IIC2	106–118	**Sand;** light brownish-gray (2.5Y 6/2 moist) and dark grayish brown (2.5Y 4/2 moist); stratified; loose moist; nonsticky and nonplastic wet; abrupt smooth boundary.
IIC3	118–133	**Loam;** light olive-brown (2.5Y 5/4 moist); partially stratified; few fine tubular pores; very friable moist; nonsticky and nonplastic wet; abrupt smooth boundary.
IIC4	133–150	**Sand;** light brownish-gray (2.5Y 6/2 moist) and dark grayish brown (2.3Y 4/2); stratified; loose moist; nonsticky and nonplastic when wet.

Table II.3 Analytical Data for Profile of Sonatala Series

Site No.	Name of soil series	Depth (cm)	Particle Size (%)			pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
			Sand (US)	Silt (US)	Clay		%	meq/100g			µg/g							
16	Sonatola	0–11	27	50	23	7.0	0.7	8.7	3.2	0.19	36	8	18	0.5	1.8	17	8	1.2
		11–32	27	48	25	7.3	0.7	9.0	3.6	0.10	50	4	10	0.4	2.7	26	11	0.9
		32–56	25	48	27	7.3	0.6	8.9	3.6	0.10	43	7	10	0.3	2.9	41	21	0.8
		56–80	35	48	17	7.3	0.7	9.4	3.3	0.11	36	8	10	0.5	1.8	37	10	1.0
		80–106	29	56	15	7.3	0.2	8.0	2.2	0.11	36	7	10	0.3	1.6	11	7	1.1
		106–118	89	8	3	7.3	0	4.3	0.9	0.06	33	3	10	0.3	1.2	1	5	2.6
		118–133	45	44	11	5.8	0	7.3	2.3	0.12	36	6	10	0.5	1.2	2	16	1.3
		133–150	97	0	3	6.4	0	1.8	0.5	0.03	33	2	10	0.5	1.0	3	5	0.5

200

Soil series		**Dhamrai**
Location		Longitude 089⁰49.1633E Latitude 24⁰44.7183N
Sample site no.		15
Village		Char Dasherbari, P.S. Sharishabari
Physiography		Young Jamuna floodplain
Relief and position		Lower part of nearly level ridges
Drainage		Poor. Seasonally flooded between 180–210 cm for a period of 4–5 months
Land Use		Mustard–Boro (HYV)

Horizon	**Depth (cm)**	**Description**
Ap1	0–8	**Loam;** gray (5Y 5/1 moist); massive; friable moist; slightly sticky, slightly plastic wet; many roots; iron staining along root channels; clear smooth boundary.
Ap2	8–12	**Silt loam;** olive-gray (5Y 5/2 moist); massive; firm moist; slightly sticky, slightly plastic wet; common roots; clear smooth boundary.
B21	12–30	**Clay loam;** olive (5Y 5/3 moist); few fine distinct olive-brown (2.5Y 5/6 moist) mottles; weak to moderate coarse to medium prismatic breaks into weak coarse subangular blocky; many very fine to fine tubular pores; firm moist; sticky and plastic wet; gradual smooth boundary.
B22	30–47	**Silt loam;** light olive-brown (2.5Y 5/4 moist) with common fine distinct strong brown (10YR 5/8 moist) mottles; weak coarse to medium prismatic; many very fine to fine tubular pores; firm moist; sticky and plastic wet; nearly continuous medium gray coatings along ped faces; clear smooth boundary.
B23	47–70	**Silt loam;** light olive-brown (2.5Y 5/4 moist) with few fine distinct yellowish brown (10YR 5/6 moist) mottles; weak coarse prismatic structure with common fine tubular pores; friable moist; slightly sticky and slightly plastic wet; nearly continuous gray cutans along ped faces; abrupt smooth boundary.
C1	70–86	**Sandy loam;** olive (5Y 4/3 moist); massive; very sticky and very plastic wet; abrupt smooth boundary.
C2	86–120	**Loam;** olive-brown (2.5Y 4/4 moist); stratified; slightly sticky and slightly plastic wet.
C3	120–150	**Silt loam;** light olive-brown (2.5Y 5/4 moist).

Table II.4 Analytical Data for Profile of Dhamrai Series

Site No.	Name of soil series	Depth (cm)	Particle Size (%)			pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
			Sand (US)	Silt (US)	Clay		%	meq/100g			µg/g							
15	Dhamrai	0-8	47	34	19	7.5	0.6	7.0	2.2	0.09	36	15	20	0.4	2.0	20	8	0.7
		12-30	23	48	29	7.7	0.7	7.4	2.8	0.10	59	11	12	0.7	1.7	44	8	1.5
		30-47	13	62	25	7.7	0.2	7.0	3.1	0.11	40	10	13	0.4	1.7	34	11	0.8
		47-70	27	56	17	7.7	0.2	8.0	3.0	0.09	33	11	10	0.4	1.6	23	4	0.9
		70-86	79	12	9	7.7	0.2	6.0	1.9	0.03	33	7	10	0.1	0.7	3	3	0.7
		86-120	45	42	13	7.8	0.2	7.5	2.4	0.11	20	6	10	0.3	1.2	14	4	0.9
		120-150	25	56	19	6.9	0.4	8.4	2.9	0.22	33	11	19	0.3	2.6	52	6	0.8

Soil series	**Dhamrai/Sabhar Bazar**
Location	Longitude 089°49.4635E Latitude 24°45.4865N
Sample site no.	21
Village	Nagda, P.S. Sharishabari
Physiography	Old Jamuna floodplain
Relief and position	Nearly level basin
Drainage	Poor. Seasonally flooded up to 180–200 cm deep for about 5 months
Land use	Mustard–Boro(HYV)

Horizon	**Depth (cm)**	**Description**
Ap1	0–9	**Clay loam;** dark grayish-brown (2.5Y 4/2 moist); massive, breaks into cloddy structure; few fine tubular pores; firm moist; sticky and plastic wet; iron staining along root channels; gleyed (NG/dark gray); few roots; abrupt smooth boundary.
Ap2	9–13	**Clay loam;** light olive-brown (2.5Y 5/4 moist) with common fine to medium distinct yellowish-brown (10YR 5/8 moist) mottles; moderate medium to fine subangular blocky structure; firm moist; sticky and plastic wet; abrupt smooth boundary.
B21	13–29	**Clay;** dark gray (5Y 4/1 moist) with common fine to medium strong brown (7.5YR 5/8 moist) mottles; moderate medium to fine prismatic structure; many fine tubular pores; firm moist; sticky and plastic wet; nearly continuous gray coatings along ped faces; clear smooth boundary.
B22	29–43	**Clay loam;** dark gray(5Y 4/1 moist) with many fine to medium distinct light-olive brown (2.5Y 5/6 moist) mottles; moderate medium prismatic breaks into subangular blocky structure; very fine tubular pores; friable moist; sticky and plastic wet; nearly continuous gray coatings along ped faces; clear smooth boundary.
B23	43–65	**Loam;** light olive-brown (2.5Y 5/4 moist) with few fine distinct yellowish-brown (10YR 5/6) mottles; weak coarse to medium prismatic breaks into weak coarse to medium subangular blocky structure; many fine tubular pores; friable moist; slightly sticky and slightly plastic wet; abrupt smooth boundary.
C1	65–88	**Sand;** gray (5Y 5/1 moist); single grained; loose moist, nonsticky and nonplastic wet.
IIC2	88–122	**Silt loam;** grayish-brown (2.5Y 5/2 moist); sticky and plastic wet.
	122–140	**Loamy sand**

N.B. Groundwater table at 90 cm. Below 88 cm, samples were collected by auger.
This profile is considered to be transitional between Dhamrai series (silty clay loam or clay loam in B horizon) and Sabhar Bazar series (silty clay or clay in B horizon).

Table II.5 Analytical Data for Profile of Dhamrai/Sabhar Bazar Series

Site No.	Name of soil series	Depth (cm)	Particle Size (%)			pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
			Sand (US)	Silt (US)	Clay		%	meq/100g			µg/g							
21	Dhamrai/ Sabhar Bazar	0–9	37	34	29	5.9	1.1	9.5	3.1	0.17	83	22	20	0.6	4.5	289	89	1.1
		9–13	35	32	33	6.9	0.6	9.6	3.2	0.15	66	8	12	0.3	2.7	75	12	1.2
		13–29	33	26	41	7.1	0.6	8.3	3.4	0.15	36	8	10	0.3	2.6	60	6	0.8
		29–43	25	38	37	7.2	0.4	8.4	3.2	0.09	36	19	8	0.3	2.1	46	4	0.8
		43–65	47	40	13	7.1	0.2	7.0	2.2	0.04	50	14	10	0.3	0.8	28	5	0.8
		65–88	95	0	5	7.1	0	2.0	0.4	0.02	17	14	9	0.3	0.6	4	1	1.1
		88–122	27	58	15	7.1	0	7.0	2.1	0.05	66	8	10	0.3	1.2	26	3	0.8

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Soil series	**Sabhar Bazar**
Location	Longitude 089°53.7303E Latitude 24°24.6909N
Sample site no.	12
Village	Jadurpara, P.S. Kalihati
Physiography	Old Jamuna floodplain
Relief and position	Nearly level basin
Drainage	Poor. Seasonally flooded up to 80-90 cm deep for about 4 months.
Land use	Mustard-Boro(HYV)

Horizon	Depth (cm)	Description
Ap	0-7	**Clay loam;** light brownish-gray (2.5Y 6/2 moist) with many fine prominent strong brown (7.5YR 5/6 moist) mottles; massive; common fine to very fine tubular pores; firm moist; sticky and plastic wet; cracks 1-2 cm wide at surface; common roots; abrupt smooth boundary.
Ap2	7-10	**Clay;** dark grayish-brown (2.5Y N4 moist) with fine prominent strong brown (7.5YR 5/6 moist) mottles; massive; few fine tubular pores; very firm moist; sticky and plastic wet; abrupt smooth boundary.
B21	10-22	**Clay;** dark gray (5Y 4/1 moist) with many medium distinct light olive-brown (2.5Y 5/6 moist) mottles; strong medium prismatic breaks into strong medium subangular and angular blocky structure; many very fine tubular pores; firm moist; sticky and plastic wet; clear smooth boundary.
B22	22-39	**Clay;** dark gray (5Y 4/1 moist) with many medium prominent yellowish-brown (10YR 5/8 moist) mottles; strong medium prismatic structure breaks into strong medium subangular and angular blocky; many very fine tubular pores; very firm moist; sticky and plastic wet; continuous thick gray (5Y 5/1) coatings along ped faces; clear smooth boundary.
B23	39-64	**Clay loam;** gray (5Y 5/1 moist) with many medium prominent yellowish-brown (10YR 5/8 moist) mottles; strong medium subangular and angular blocky structure; common fine tubular pores; very firm moist; sticky and plastic wet; continuous thick dark gray (5Y 4/1) coatings along ped faces; clear smooth boundary.
B3	64-77	**Sandy clay loam;** dark grayish-brown (2.5Y 4/2 moist) and light olive-brown (2.5Y 5/6 moist); moderate coarse to medium prismatic structure breaks into moderate medium subangular blocky; common very fine tubular pores; firm moist; sticky and plastic wet; common manganese concretions; abrupt smooth boundary.
C1	77-146	**Sandy loam;** light olive-brown (2.5Y 5/4 moist); weak coarse to medium prismatic structure; many very fine tubular pores; friable moist; slightly sticky and slightly plastic wet; common manganese concretions.

Table II.6 Analytical Data for Profile of Sabhar Bazar Series

Site No.	Name of soil series	Depth (cm)	Particle Size (%)			pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
			Sand (US)	Silt (US)	Clay		%	meq/100g			μg/g							
12	Sabhar Bazar	0–7	28	36	36	5.5	2.5	8.4	2.9	0.12	83	10	40	Trace	6.7	754	67	1.0
		7–10	22	32	46	5.9	1.5	9.7	3.0	0.06	83	8	6	Trace	4.7	800	37	1.0
		10–22	14	38	48	6.3	1.1	10.4	3.4	0.05	83	6	10	Trace	2.5	112	13	0.9
		22–39	14	34	52	6.6	0.8	11.1	4.4	0.06	83	8	9	Trace	3.6	130	4	0.9
		39–64	38	30	32	6.8	0.6	10.5	3.5	0.10	83	8	7	0.13	3.1	359	4	0.9
		64–77	50	24	26	6.8	0.4	9.7	2.9	0.06	83	6	10	Trace	1.7	93	9	1.0
		77–146	74	12	14	6.8	0.2	5.9	1.5	0.01	33	8	4	0.05	0.2	10	1	0.1

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Soil series	**Ghatail**
Location	8/15–10 (SRDI airphoto reference)
Village	Sadhurpara Golgonda, P.S. Ghatail
Physiography	Old Brahmaputra floodplain
Relief and position	Basin
Drainage	Poor. Seasonally flooded to moderate or great depth (>90 cm)
Land use	B.aman-khesari/fallow

Horizon	**Depth (cm)**	**Description**
Ap1	0–5	**Silty clay;** very dark gray (2.5Y 3/1 moist) with common fine distinct dark brown (7.5YR 4/4) mottles; moderate coarse and medium cloddy and medium and fine granular structure; common fine tubular pores; plastic; nonsticky moist; many fine roots; abrupt smooth boundary.
Ap2	5–10	**Clay;** very dark gray (2.5Y 3/1 moist) with common fine distinct dark brown (7.5YR 4/4) mottles; massive; few fine tubular pores; plastic, nonsticky moist; many fine roots; abrupt wavy boundary.
A3	10–20	**Clay;** dark gray (5Y 4/1 moist) with common fine distinct dark yellowish-brown (10YR 4/4) mottles; moderate coarse angular blocky structure; common fine tubular pores; medium nearly continuous dark gray coatings along vertical and horizontal ped faces and pores; plastic and nonsticky moist; common fine roots; clear smooth boundary.
B2	20–66	**Clay;** dark gray (5Y 4/1 moist) with many fine distinct dark brown (10YR 4/3) mottles; strong very coarse prismatic and moderate very coarse angular blocky structure in upper part; few fine tubular and few fine vesicular pores; thick continuous dark gray coatings along vertical and horizontal ped faces and pores; slightly firm moist; few fine roots, and common fine roots on ped faces; clear wavy boundary.
B3	66–89	**Silty clay;** dark grayish-brown (2.5Y 4/2 moist) with many medium distinct yellowish-brown (10YR 5/8) mottles; moderate very coarse prismatic and weak coarse angular blocky structure; common fine tubular pores; medium nearly continuous dark gray coatings along vertical and horizontal ped faces and pores; slightly firm moist; gradual boundary.
C1	89–114	**Clay;** dark gray (10YR 4/1 wet) finely mottled dark yellowish brown; moderate very coarse prismatic structure; few fine tubular pores; medium continuous coatings along vertical ped faces and pores; plastic and slightly sticky wet; clear smooth boundary.
IIC2	114–127	**Clay loam;** gray (5Y 5/1 wet) with many fine distinct yellowish-brown (10YR 5/6) mottles; massive; few fine tubular pores; thin continuous coatings along pores; consistence not recorded.

N.B: Profile description from Reconnaissance Soil Survey report, Tangail Subdivision (SRDI 1967).

Table II.7 Analytical Data for Profile of Ghatail Series

Depth (cm)	Particle Size (%)			Exchangeable cations, meq/100g							TEB	BSP	pH	Percent		
	Sand (US)	Silt (US)	Clay	CEC	Ca	Mg	K	Na	H	Total				C	N	C/N
0–5	16	43	41	20.3	8.8	1.5	0.27	0.13	6.5	17.20	10.70	62	5.3	2.22	0.17	13
5–10	21	38	41	19.7	13.6	2.8	0.13	0.13	2.7	19.36	16.66	86	5.9	1.59	0.12	13
10–20	18	34	48	23.7					2.4				6.7	1.07	0.08	13
20–66	12	33	55	30.8									6.8			
66–89	11	49	40	26.4									7.1			
89–114	33	27	40	22.3									6.9			
114–127	36	36	28	16.9									7.1			

N.B: Laboratory data from reconnaissance soil survey report, Tangail Subdivision (SRDI, 1967). N data represent total nitrogen, not NH_4 nitrogen reported for study samples from other floodplains.

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Appendix III

FAP 19 FLOODPLAIN SEDIMENTATION LITERATURE SURVEY
Ordered by (1) topic (2) date

GENERAL STUDIES

Harwood, K.; Brown, A. G. 1993. Fluvial processes in a forested anastomosing river; flood partitioning and changing flow patterns. *Earth Surface Processes and Landforms* 18 (8):741–748.

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Appendix IV
Tabulated Data for Sediment and Water Samples

Table IV.1a Physical Characteristics of Sample Sites, Sharishabari

Site No.	Physiographic Unit	Relief and Position	Soils: Series	Soils: Subsoil Texture	Normal Flooding: Depth (cm)	Normal Flooding: Duration (days)	Cropping Pattern (1993)	Fertilizers Used (1993) kg/ha
14	AJF	US of VGU levee	Melandaha	Silt loam	70–90	120	Jute-Wheat	Urea - 225 TSP - 37 MP - 19
15	YJF	LS of NL ridges	Dhamrai	Clay loam	180–210	130	Mustard-Boro(H)*	Urea - 524 TSP - 412 MP - 74 $ZnSo_4$ - 7 Gypsum - 75
16	YJF	US of VGU ridges	Sonatola	Silt loam	60–90	120	T.Aman(L)-Wheat	Urea - 262 TSP - 75 MP - 37
17	YJF	US of VGU ridges	Melandaha	Silt loam	60–90	125	T.Aman(L)-Wheat	Urea - 337 TSP - 150 MP - 37
18	YJF	VGU basin	Dhamrai	Clay loam	90–130	130	T.Aman(L)-Boro(H)*	Urea - 524 TSP - 112 MP - 37
19	AJF	US of VGU ridges	Silty Jamuna alluvium	Silt loam	60–100	90	Jute-T.Aman(L)-Wheat	Urea - 315 TSP - 75 MP - 37
20	AJF	MS of VGU ridges	Melandaha	Silt loam	100–120	120	Jute-T.Aman(L)-Wheat	Urea - 561 TSP - 112
21	OJF	NL basin	Sabhar bazar	Clay	180–200	150	Mustard-Boro(H)*	Urea - 250 TSP - 262 MP - 150
22	AJF	US of VGU levee	Melandaha	Silt loam	90–120	90	Sugarcane	Urea - 150 TSP - 75 MP - 37
23	OJF	LS of VGU ridges	Silmondi	Silty clay loam	120–160	95	T.Aman(L)-Boro(H)*	Urea - 486 TSP - 150 MP - 75 $ZnSo_4$ - 11 Gypsum - 75
24	AJF	Infilled channel	Sandy Jamuna alluvium	Sand	300–450	125	Mix Seasamum & Kaon-T.Aman(L)	Urea - 150
25	AJF	LS of VGU levee	Silty Jamuna alluvium	Silt loam	180–200	105	Jute-T.Aman(L)-Black gram	Urea - 262
26	AJF	LS of VGU levee	Silty Jamuna alluvium	Silt loam	210–240	105	Mustard-Boro(H)*	Urea - 411 TSP - 168 MP - 56 Gypsum - 93

Abbreviations:

Physiography
AJF: Active Jamuna floodplain
YJF: Young Jamuna floodplain
OJF: Older Jamuna floodplain

Relief and position
US: Upper slope
MS: Middle slope
LS: Lower slope
VGU: Very gently undulating
NL: Nearly level

Cropping patterns
L: Low-yield variety
H: High-yield variety
*: Irrigated

Table IV.1b Physical Characteristics of Sample Sites, Kalihati

Site No.	Physiographic Unit	Relief and Position	Soils: Series	Soils: Subsoil Texture	Normal Flooding: Depth (cm)	Normal Flooding: Duration (days)	Cropping Pattern (1993)	Fertilizers Used (1993) kg/ha
7	AJF	US of VGU ridges	Melandaha	Silt loam	90-120	120	Mix aus & aman - Wheat	Urea - 262 TSP - 150 MP - 19
8	YJF	MS of VGU ridges	Melandaha	Silt loam	90-100	120	Jute-T.Aman-Wheat	Urea - 486 TSP - 75 MP - 37 SSP - 45
9	YJF	LS of VGU ridges	Dhamrai	Clay loam	120-160	100	Mix aus & aman-pulses	Urea - 412 TSP - 112 MP - 19
10	YJF	LS of NL-VGU ridges	Dhamrai	Clay loam	120-170	120	T.aman(L)-Mustard	Urea - 240 TSP - 37 SSP - 150
11	YJF	MS of NLridges	Melandaha	Silt loam	100-120	105	B.aus-T.aman(L)-Black gram	Urea - 300
12	OJF	NL basin	Sabhar basar	Clay	80-90	120	Mustard-Boro(H)*	Urea - 411 TSP - 165 MP - 89
13	AJF	MS of VGU levee	Silty Jamuna alluvium	Silt loam	210-220	130	Jute-T.aman(L)-Onion	Urea - 374 TSP - 150 MP - 19
1	AJF	US of VGU ridges	Melandaha	Silt loam	90-120	105	Mix aus & aman-pulses	Urea - 262 TSP - 752 MP - 37
2	AJF	LS of NL ridges	Dhamrai	Clay loam	110-130	120	Mix aus & aman-Wheat	Urea - 150 TSP - 56 MP - 19
3	AJF	MS of VGU ridges	Melandaha	Silt loam	110-120	120	Jute-T.aman(LO-wheat	Urea - 352 TSP - 56 MP - 19
4	OJF	LS of VGU-GU ridges	Dhamrai	Clay loam	90-120	120	T.D.aman-mustard-boro(H)*	Urea - 659 TSP - 112 MP - 37 SSP - 120
5	AJF	MS of VGU levee	Sandy Jamuna alluvium	Sandy loam	180-200	120	Mix aus & aman-Black gram	Urea - 75
6	AJF	Infilled channel	Silty Jamuna alluvium	Silt loam	240-270	110	Mix aus & aman-Wheat	Urea - 150 TSP - 37 MP - 15

Abbreviations:

Physiography
AJF: Active Jamuna floodplain
YJF: Young Jamuna floodplain
OJF: Older Jamuna floodplain

Relief and position
US: Upper slope
MS: Middle slope
LS: Lower slope
VGU: Very gently undulating
NL: Nearly level

Cropping patterns
L: Low-yield variety
H: High-yield variety
*: Irrigated

Table IV.2a Analytical Data for Sediment Deposited in Traps

Site No.	Phys. Unit	Topographic Position	Texture	pH	OM	EC	Ca	Mg	K	NH$_4$	P	S	B	Cu	Fe	Mn	Zn
					%	ds/m	meq/100gm soil			μg/gm							
7	AJF	US of ridges	-	7.4	4.5	0.47	7.9	1.7	0.28	173	65	106	0.21	2.9	599	276	6.2
3	AJF	MS of ridges	-	7.3	3.8	0.43	6.5	1.6	0.20	115	22	118	0.40	1.6	164	54	3.1
2	AJF	LS of ridges	-	7.3	5.2	0.64	8.0	1.7	0.35	173	52	182	0.27	1.4	230	60	4.4
8	YJF	MS of ridges	Loam	6.8	0.9	0.14	7.6	2.2	0.20	72	18	33	0.33	5.3	309	150	2.9
10	YJF	LS of ridges	Clay loam	6.6	1.6	0.25	8.8	1.9	0.45	133	61	55	0.37	7.1	248	181	4.2

Table IV.2b Analytical Data for Sediment Deposited on Cloth

Site No.	Phys. Unit	Topographic Position	Texture	pH	OM	EC	Ca	Mg	K	NH$_4$	P	S	B	Cu	Fe	Mn	Zn
					%	ds/m	meq/100gm soil			μg/gm							
5	AJF	MS of levee	Silty clay loam	6.9	2.0	0.60	7.6	1.8	0.20	108	15	143	0.24	3.1	115	52	1.2
26	AJF	LS of levee	Clay loam	7.0	5.2	0.47	7.3	1.9	0.48	201	27	85	0.50	2.2	148	72	0.8
25	AJF	LS of levee	Silty clay loam	6.9	4.2	0.28	7.7	1.8	0.30	151	19	36	0.53	2.0	100	76	0.7
24	AJF	Infilled channel	Sand	6.9	0.2	0.10	4.2	1.3	0.05	13	6	19	0.36	0.1	15	4	0.4
13	AJF	MS of levee	Silt loam	7.1	3.4	1.90	9.1	1.9	0.42	187	13	303	0.62	2.1	50	34	0.6
6	AJF	Infilled channel	Silt loam	6.7	2.1	0.20	5.9	1.9	0.20	87	12	54	0.20	2.3	234	100	0.9

Table IV.2c Analytical Data for Sediment Deposited on Mats

Site No.	Phys. Unit	Topographic Position	Texture	pH	OM	Ec	Ca	Mg	K	NH$_4$	P	S	B	Cu	Fe	Mn	Zn
					%	ds/m	meq/100gm soil			μg/gm							
24	AJF	LP of levee	Loam	6.9	5.2	0.3	8.4	1.9	0.46	173	15	94	0.53	2.2	117	67	0.7
25	AJF	LP of levee	Loam	6.9	5	0.22	8	1.9	0.31	152	11	43	0.39	2.1	103	74	1
5	AJF	MP of levee	Silt loam	7.2	4.8	0.56	7.9	1.8	0.3	130	12	151	0.56	2	163	48	0.8
13	AJF	MP of levee	Loam	7.1	4.5	1.6	8.9	1.9	0.48	216	46	303	0.53	2	70	5	0.4
6	AJF	Infilled channel	Silt loam	8.9	3.5	0.16	5.9	1.9	0.28	76	10	41	0.21	2.4	352	134	0.5

Table IV.3 Analytical Data of Topsoils of Sampling Site, Sharishabari

Site No.	Physio-graphic unit	Name of soil series	Land type	Texture	pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
						%	meq/100gm			µg/gm							
14	AJF	Melandaha	Medium high land	Loam	7.2	0.33	6.33	1.66	0.12	25	12	17	0.4	2.7	52	13	0.9
20	AJF	Ditto	Medium low land	Loam	7.7	0.43	8.4	1.63	0.22	34	4	10	0.3	2.5	258	52	0.7
22	AJF	Ditto	Ditto	Sandy loam	6.5	0.10	4.9	1.1	0.05	29	8	8	0.3	0.7	18	7	0.9
19	AJF	Silty allu-vium	Medium high land	Loam	7.7	1.3	5.5	0.9	0.17	33	5	11	0.3	3.0	458	15	0.8
25	AJF	Ditto	Low land	Sandy loam	6.8	0.40	4.6	0.8	0.06	27	15	10	0.4	1.9	27	40	0.7
26	AJF	Ditto	Ditto	Loam	6.9	0.40	5.0	1.6	0.07	33	11	20	0.4	1.7	30	16	0.7
24	AJF	Sandy allu-vium	Low land	Sand	6.3	0	2.4	0.3	0.02	13	7	17	0.4	0.7	7	5	0.8
17	YJF	Melandaha	Medium high land	Loam	7.5	0.8	8.5	1.4	0.13	21	5	8	0.6	2.8	55	15	0.7
16	YJF	Sonatola	Medium high land	Loam	7.6	1.0	8.6	2.9	0.15	22	24	10	0.4	3.1	69	13	0.9
18	YJF	Dhamrai	Medium low land	Clay loam	7.6	1.1	8.9	2.9	0.16	52	4	5	0.3	3.5	358	18	0.9
15	YJF	Ditto	Low land	Loam	7.6	0.8	7.6	1.9	0.20	21	14	8	0.5	3.0	94	24	0.8
23	OJF	Silmondi	Medium low land	Clay loam	6.3	1.3	7.0	2.8	0.05	57	20	8	0.3	2.6	270	25	1.1
21	OJF	Sabhar bazar	Low land	Clay loam	6.7	1.0	9.0	2.3	0.07	35	20	11	0.3	1.8	245	59	0.7

Table IV.4 Analytical Data of Topsoils of Sampling Sites, Kalihati

Site No.	Physio-graphic unit	Name of soil series	Land type	Texture	pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
						%	meq/100gm			µg/gm							
7	AJF	Melandaha	Medium low land	Loam	7.2	0.9	7.1	2.1	0.12	27	8	12	0.3	2.2	56	19	0.7
1	AJF	Ditto	Ditto	Loam	6.7	1.0	7.3	1.8	0.12	7	18	41	0.4	2.8	35	13	0.5
3	AJF	Ditto	Ditto	loam	7.2	0.8	7.0	2.3	0.11	58	15	2	0.5	3.0	56	20	0.7
2	AJF	Dhamrai	Medium low land	Clay loam	7.2	1.1	9.6	3.8	0.13	33	12	2	0.1	3.6	93	35	0.7
5	AJF	Sandy allu-vium	Low land	Sandy loam	6.5	0.8	7.3	1.2	0.10	59	22	57	0.2	3.3	59	53	0.8
13	AJF	Silty allu-vium	Low land	Loam	5.9	0.9	7.7	1.4	0.12	12	10	7	0.4	3.3	54	36	0.6
6	AJF	Ditto	Ditto	Silt loam	6.9	0.8	6.7	1.3	0.22	53	22	23	0.3	5.9	234	142	1.7
8	YJF	Melandaha	Medium low land	Loam	6.8	1.0	8.0	3.4	0.12	31	16	2	0.3	4.4	261	100	0.9
11	YJF	Ditto	Ditto	Silt loam	6.4	1.0	8.2	3.1	0.12	7	12	6	0.6	3.0	60	19	0.6
9	YJF	Dhamrai	Medium low land	Silt loam	6.8	0.8	7.6	3.0	0.19	29	17	11	0.3	3.7	106	27	0.8
10	YJF	Ditto	Ditto	Clay loam	6.3	1.4	7.9	3.3	0.11	34	15	12	0.4	2.7	68	25	0.7
12	OJF	Sabhar bazar	Medium high land	Clay loam	6.5	2.5	8.7	2.9	0.08	28	16	12	0.3	5.0	188	46	0.7
4	OJF	Dhamrai	Medium low land	Clay loam	6.8	1.8	8.7	3.6	0.07	61	13	5	0.1	4.0	187	30	0.9

Table IV.5 Analytical Data of the First Three Layers of Soil Profiles, Sharishabari

Site No.	Phys. unit	Name of soil series	Land type	Depth (cm)	Texture	pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
							%	meq/100 gm			μg/gm							
14	AJF	Melandaha	Medium Highland	0-12	Loam	6.3	0.6	5.3	1.6	0.14	33	8	10	0.5	2.0	18	14	1.0
				12-29	Loam	7.2	0.2	5.7	2.0	0.14	33	7	10	1.0	2.8	47	14	1.0
				29-51	Loam	7.2	0.2	5.7	2.0	0.10	33	7	15	0.6	2.8	46	26	0.8
20	AJF	Ditto	Medium Lowland	0-9	Loam	7.3	0.4	3.2	0.7	0.09	33	8	10	0.3	2.0	23	9	1.0
				9-24	Silt loam	7.5	0.6	6.0	1.0	0.09	36	11	8	0.5	2.3	17	13	1.5
				24-44	Sandy loam	7.5	0	3.1	0.5	0.02	33	10	10	0.4	0.4	2	2	1.2
19	AJF	Silty alluvium	Medium Highland	0-12	Loam	7.2	0.6	5.9	0.9	0.16	36	8	10	0.2	2.6	30	11	0.7
				12-21	Loam	7.2	0.6	5.9	1.0	0.14	33	14	12	0.5	2.4	26	17	0.7
				21-43	Silt loam	7.4	0.4	5.6	0.7	0.06	59	7	8	0.3	1.5	9	6	0.5
16	YJF	Sonatola	Medium Highland	0-11	Silt loam	7.0	0.7	8.7	3.2	0.19	36	8	18	0.5	1.8	17	8	1.2
				11-32	Loam	7.3	0.7	9.0	3.6	0.10	50	4	10	0.4	2.7	26	11	0.9
				32-56	Loam	7.3	0.6	8.9	3.6	0.10	43	7	10	0.3	2.9	41	21	0.8
15	YJF	Dhamrai	Lowland	0-8	Loam	7.5	0.6	7.0	2.2	0.09	36	15	20	0.4	2.0	20	8	0.7
				8-12	Silt loam	7.7	0.7	7.4	2.8	0.10	59	11	12	0.7	1.7	44	8	1.5
				12-30	Clay loam	7.7	0.2	7.0	3.1	0.11	40	10	13	0.4	1.7	34	11	0.8
21	OJF	Sabhar bazar	Lowland	0-9	Clay loam	5.9	1.1	9.5	3.1	0.17	83	22	20	0.6	4.5	289	89	1.1
				9-13	Clay loam	6.9	0.6	9.6	3.2	0.15	66	8	12	0.3	2.7	75	12	1.2
				13-29	Clay	7.1	0.6	8.3	3.4	0.15	36	8	10	0.3	2.6	60	6	0.8

Table IV.6 Analytical Data of First Three Layers of Soil Profiles, Kalihati

Site No.	Phys. unit	Name of soil series	Land type	Depth (cm)	Texture	pH	OM	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn
							%	meq/100 gm			µg/gm							
7	AJF	Melandaha	Medium Lowland	0-9	Loam	6.9	1.1	8.3	2.8	0.10	59	11	10	0.25	2.9	116	22	1.2
				9-20	Loam	7.4	0.6	7.2	1.8	0.10	59	10	2	0.05	3.3	87	25	1.5
				20-44	Sandy loam	7.4	0.2	5.5	1.2	0.04	59	3	2	0.28	2.0	41	8	1.0
3	AJF	Ditto	Ditto	0-8	Silt loam	7.2	0.8	3.8	1.5	0.10	33	7	8	0.2	2.5	56	15	0.7
				8-17	Silt loam	7.3	1.1	7.0	2.8	0.10	36	7	6	0.3	2.2	37	8	0.8
				17-30	Sandy loam	7.3	0.4	5.8	2.3	0.09	33	7	8	0.4	1.4	24	8	0.6
2	AJF	Dhamrai	Medium Lowland	0-10	Clay loam	6.7	1.1	6.8	2.2	0.07	83	8	10	Trace	1.3	30	6	0.2
				10-26	Clay loam	6.9	1.0	8.5	3.4	0.11	83	4	43	Trace	1.4	20	5	0.3
				26-56	Sandy loam	7.1	0.2	6.5	1.4	0.06	83	7	2	Trace	0.6	12	3	0.2
8	YJF	Melandaha	Medium Lowland	0-10	Loam	7.2	1.0	8.4	3.5	0.10	83	7	10	Trace	4.7	300	34	1.4
				10-18	Silt loam	7.0	0.6	6.6	3.4	0.13	83	6	2	0.25	3.3	191	23	1.0
				18-38	Loam	6.9	0.2	5.1	2.5	0.08	66	10	5	0.50	2.4	75	17	1.2
11	YJF	Ditto	Ditto	0-11	Silt loam	7.1	0.8	7.6	2.5	0.11	50	14	5	0.5	2.1	45	18	0.8
				11-30	Silt loam	7.1	0.8	6.1	2.2	0.09	33	7	5	0.6	1.7	24	7	0.7
				30-50	Sandy loam	7.2	0.4	4.8	1.7	0.05	26	8	5	0.4	1.0	8	7	0.7
12	OJF	Sabhar bazar	Medium Highland	0-7	Clay loam	5.5	2.5	8.4	2.9	0.12	83	10	40	Trace	6.7	754	67	1.0
				7-10	Clay	5.9	1.5	9.7	3.0	0.06	83	8	6	Trace	4.7	800	37	1.0
				10-22	Clay	6.3	1.1	10.4	3.4	0.05	83	6	10	Trace	2.5	112	13	0.9

Table IV.7 Dissolved Nutrients in Water from Sample Sites and Rivers

Site No.	pH	EC	Ca	Mg	K	NH_4	P	S	B	Cu	Fe	Mn	Zn	Total Quantity of Sediment (mg/l)	Total Dissolved Solids (mg/l)
			mg/l												
24*	7.3	0.118	23.6	3.4	2.7	Trace	0.31	3.4	0.26	0.25	1.32	0.11	0.21	366	17
25*	6.2	0.127	23.7	3.1	5.8	Trace	0.42	4.3	0.21	0.15	1.26	0.08	0.21	20	10
26*	7.5	0.118	22.1	3.8	3.6	Trace	0.33	4.1	0.22	0.38	1.32	0.14	0.22	33	13
5†	6.8	0.122	22.4	3.6	3.2	Trace	0.39	3.7	0.28	0.20	1.22	0.07	0.21	53	20
6†	6.1	0.115	22.1	3.5	3.1	Trace	0.37	4.0	0.26	0.16	1.79	0.13	0.22	173	27
13†	6.4	0.119	22.4	3.8	3.2	Trace	0.32	4.3	0.30	0.18	1.29	0.10	0.23	73	23
Jamuna	7.0	0.105	28.8	10.2	3.2	Trace	0.32	3.8	0.14	0.27	0.6	0.29	0.20	847	73
Dhaleswari (1)	7.0	0.104	26.3	8.7	2.7	Trace	0.21	4.2	0.17	0.16	0.43	0.23	0.20	533	97
Dhaleswari (2)	7.2	0.103	23.9	7.9	2.7	Trace	0.32	4.2	0.19	0.18	0.44	0.22	0.17	727	57

* Sharishabari site
† Kalihati site

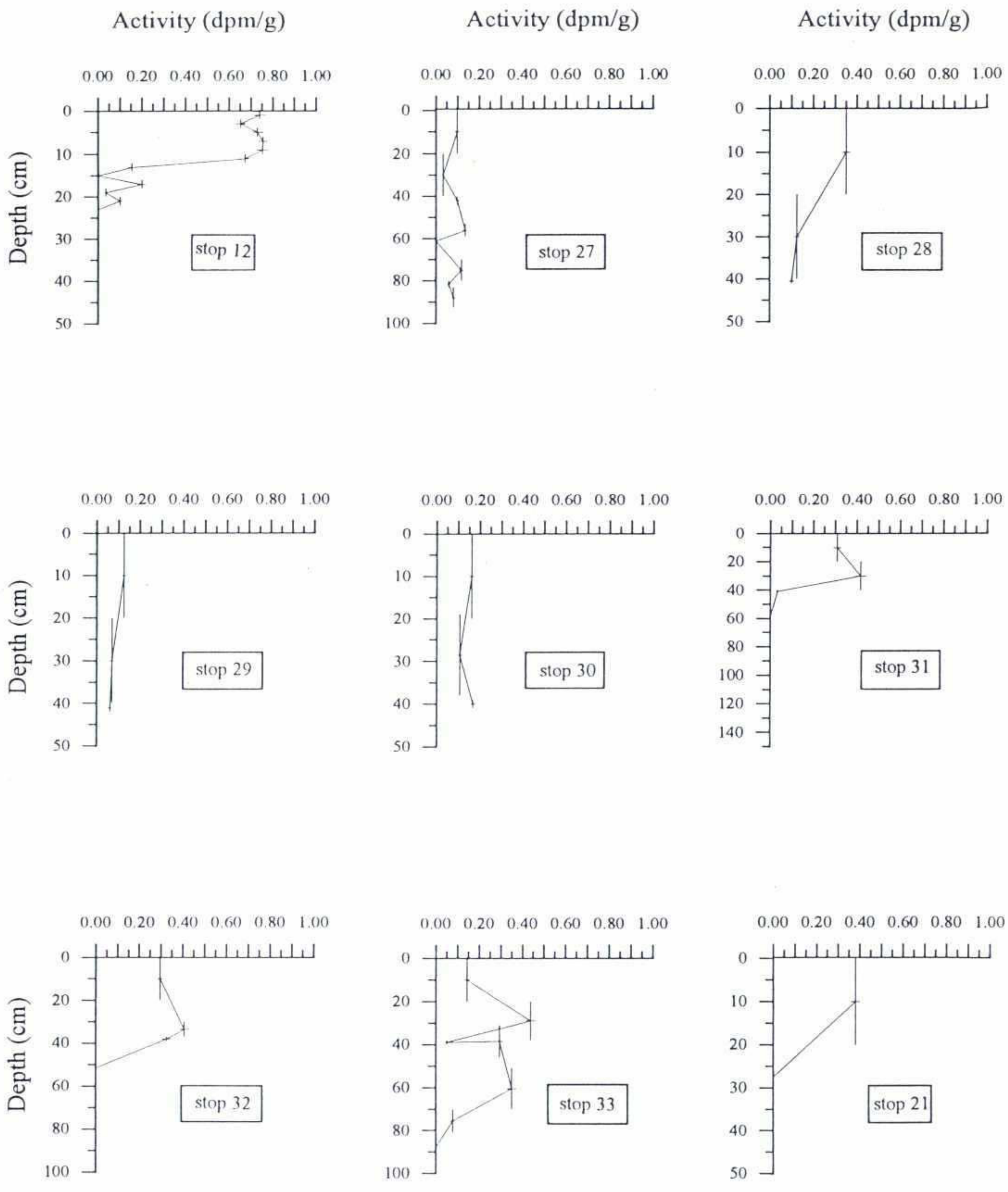

Figure IV.1 Cesium Activity (dpm/g) Versus Depth (cm)

cont. →

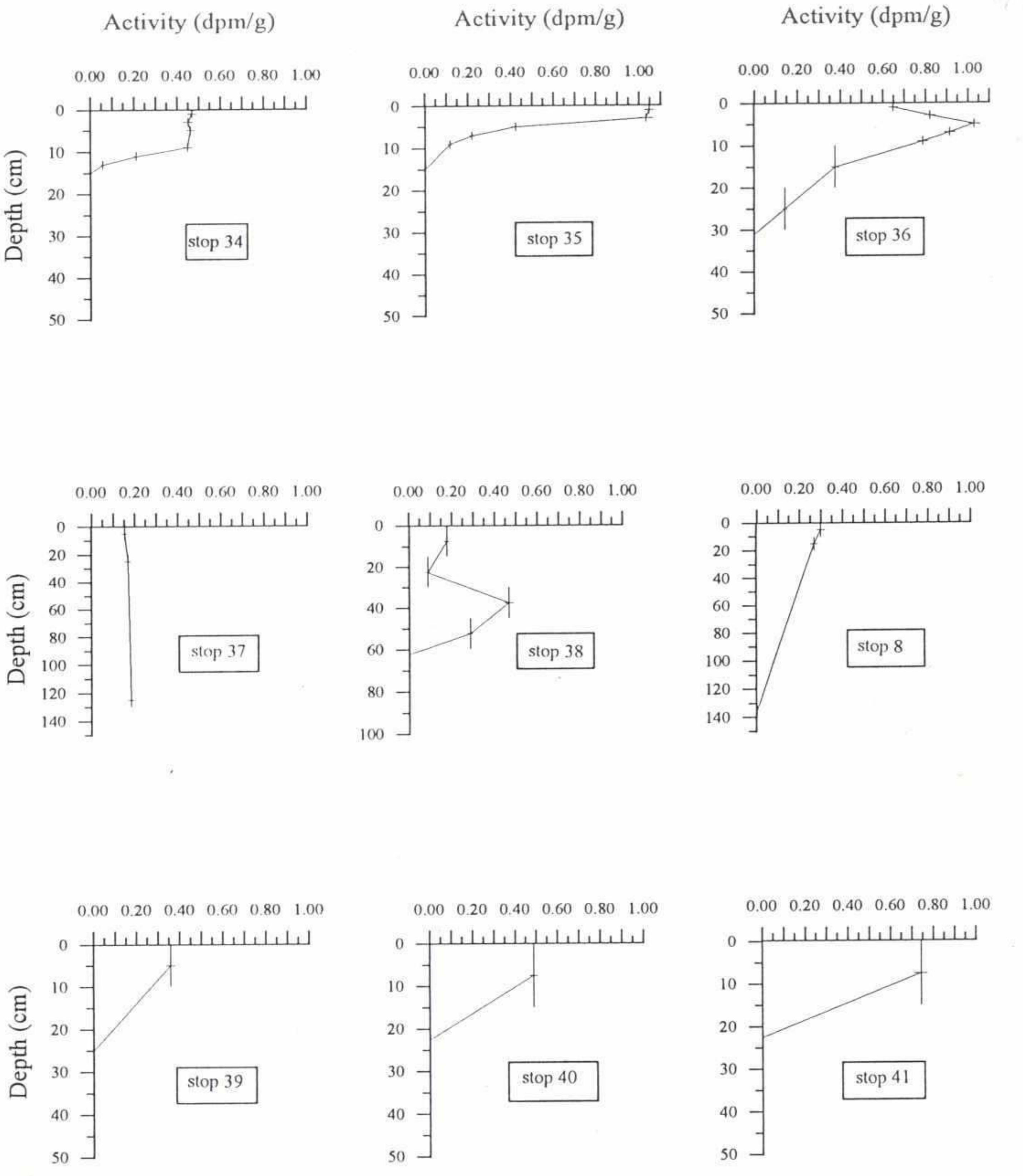

Figure IV.1 **Cesium Activity (dpm/g) Versus Depth (cm)**

cont. →

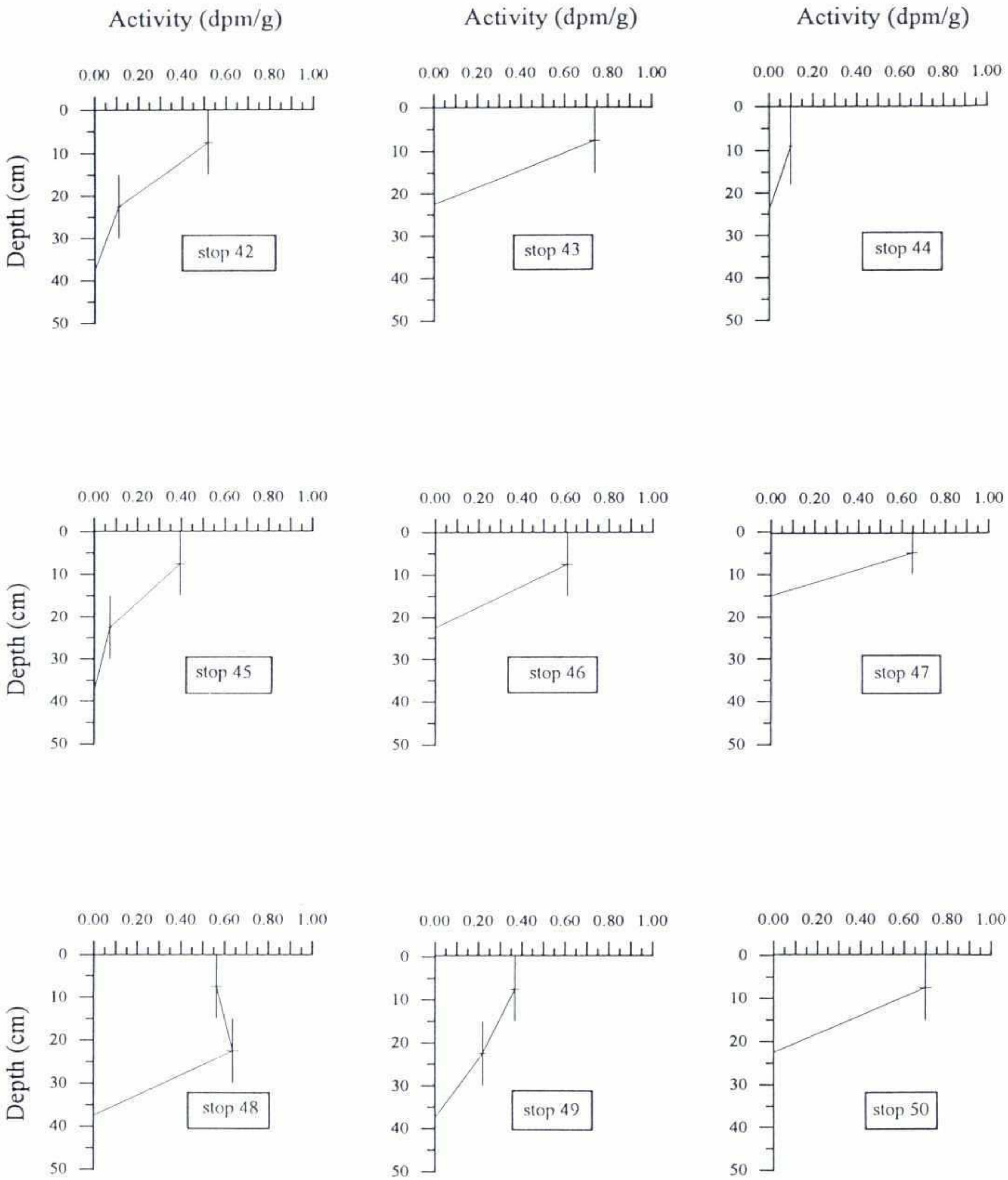

Figure IV.1 Cesium Activity (dpm/g) Versus Depth (cm)

cont. →

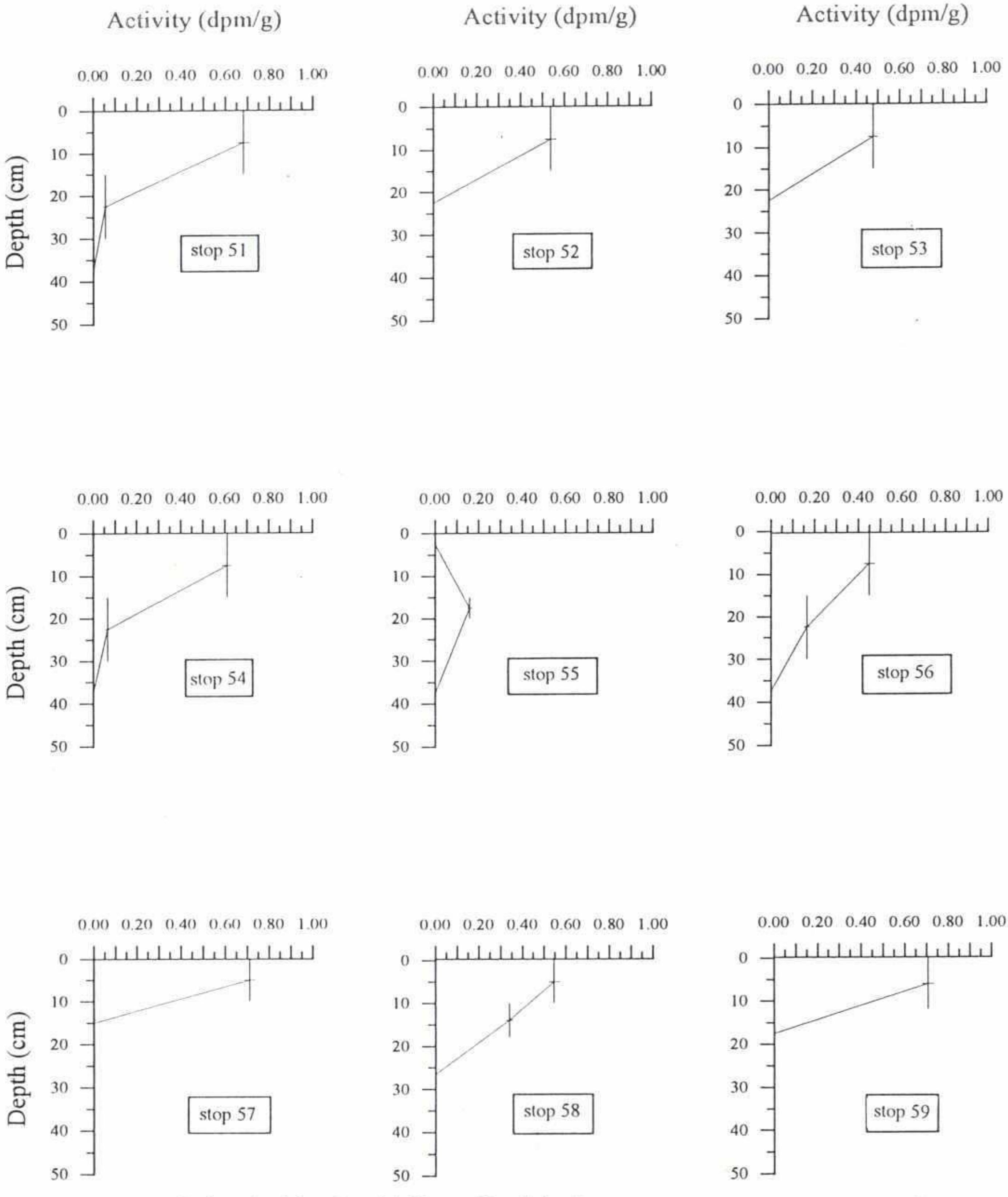

Figure IV.1 Cesium Activity (dpm/g) Versus Depth (cm)

cont. →

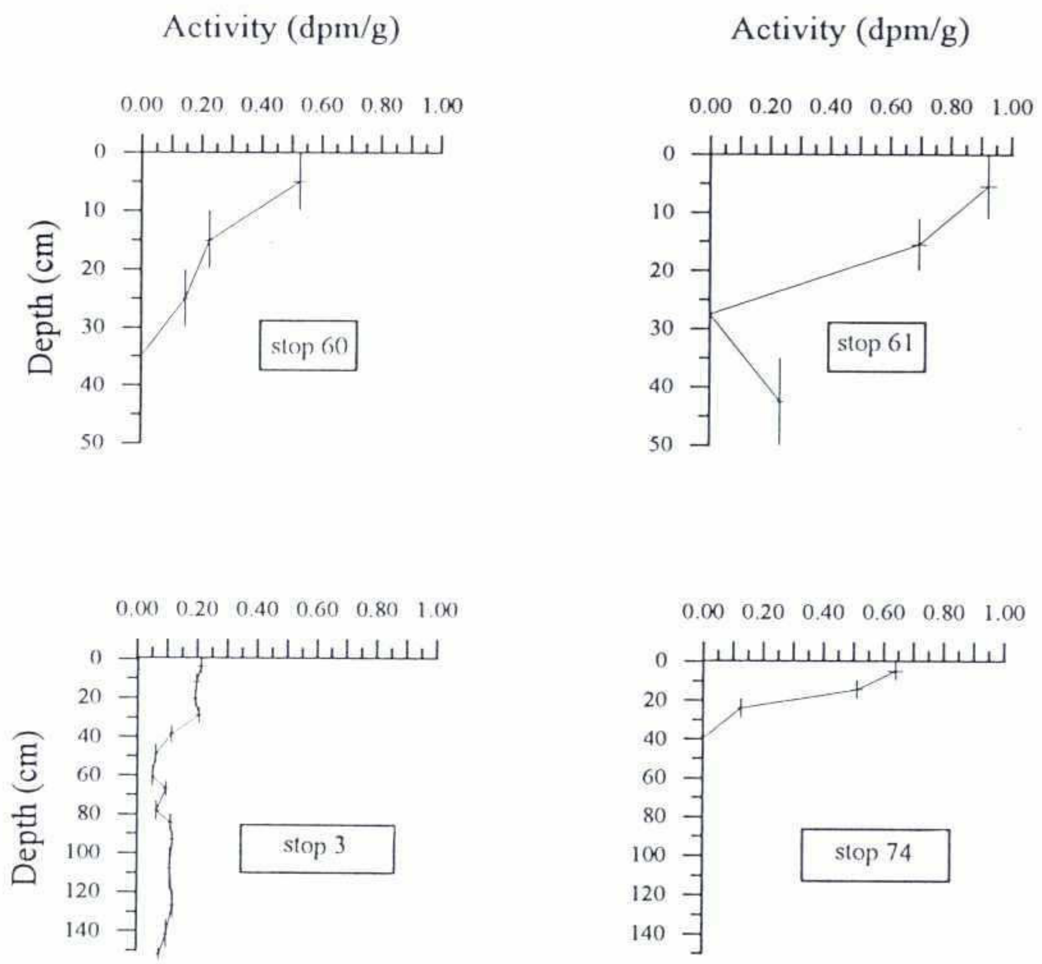

Figure IV.1 **Cesium Activity (dpm/g) Versus Depth (cm)**

Table IV.8 Results of Cesium Analysis

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
BANGLADESH:7-94															
025akal	0-7.5	RC	0.03	65.70	34.30	0.21	0.01	0.19	0.01	1.35	2.16		1.35	1.93	
025akal	7.5-16	RC	1.61	82.71	15.68	0.20	0.01	0.34	0.02	1.35	2.28		1.35	3.85	
025akal	16-24.5	RC	1.90	84.02	14.08	0.19	0.01	0.35	0.01	1.35	2.22		1.35	4.05	
025akal	24.5-34	RC	2.21	79.92	17.86	0.21	0.01	0.32	0.02	1.35	2.64		1.35	4.07	
025akal	34-44	RC	10.23	84.79	4.98	0.11	0.01	0.42	0.01	1.35	1.55		1.35	5.63	
025akal	44-55	RC	15.62	79.26	5.12	0.06	0.01	0.24	0.01	1.35	0.94		1.35	3.60	
025akal	55-63	RC	27.77	65.28	6.95	0.05	0.01	0.20	0.01	1.35	0.57		1.35	2.19	
025akal	63-73	RC	19.81	70.40	9.80	0.10	0.01	0.27	0.01	1.35	1.30		1.35	3.70	
025akal	73-80	RC	21.16	74.46	4.38	0.07	0.01	0.29	0.01	1.35	0.62		1.35	2.70	
025akal	80-89	RC	20.65	70.79	8.56	0.11	0.01	0.35	0.01	1.35	1.37		1.35	4.26	
025akal	89-97	RC	2.62	88.35	9.03	0.12	0.01	0.29	0.01	1.35	1.29		1.35	3.16	
025akal	97-119	A	4.98	88.30	6.72	0.11	0.01	0.33	0.01	1.35	3.29		1.35	9.76	
nb 025akal	119-134	A	9.97	83.28	6.75	0.12	0.01	0.38	0.01	1.35	2.45		1.35	7.66	
025akal	134-149	A	18.55	78.48	2.97	0.10	0.01	0.49	0.01	1.35	2.01		1.35	9.84	
nb 025aka	149-155	A	17.97	75.15	6.88	0.08	0.01	0.26	0.01	1.35	0.62	**25.31**	1.35	2.10	68.51
032bpr	0-9.5	RC	0.91	38.60	60.40	0.64	0.02	0.35	0.02	1.35	8.21		1.35	2.10	
032bpr	9.5-19	RC	0.31	53.35	46.34	0.51	0.02	0.44	0.02	1.35	6.57		1.35	5.67	
032bpr	19-29	RC	0.05	43.80	56.20	0.13	0.01	0.07	0.01	1.35	1.72		1.35	1.00	
032bpr	29-50	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	50-65	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	65-72	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	72-84	A				0.0000	0.0000			1.35	0.00		1.35	x	
nb 032bpr	84-96	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	96-102	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	102-114	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	114-124	A				0.0000	0.0000			1.35	0.00		1.35	x	
032bpr	124-131	A				0.0000	0.0000			1.35	0.00	**16.51**	1.35	x	8.77

LEGEND

Sampler
RC: ring core
TC: tray core
H: hand or bag sample
A: auger
CS: core sample (ring?)

Texture
L: loam
Sa: sand, sandy
Si: silt, silty
C: clay
F: fine

Note:
Δ indicates interpolated activity

Average bulk density calculated from porosity

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
BANGLADESH: 9-94															
1	0-2	6c	5.52	42.99	51.49	0.74	0.03	0.49	0.03	1.35	2.00		1.35	1.33	
1	2-4	6c	2.27	62.97	34.75	0.65	0.02	0.59	0.03	1.35	1.77		1.35	1.60	
1	4-6	6c	1.90	63.42	34.69	0.73	0.03	0.66	0.03	1.35	1.97		1.35	1.78	
1	6-8	6c	1.79	64.55	33.66	0.75	0.02	0.70	0.02	1.35	2.04		1.35	1.89	
1	8-10	6c	0.97	60.66	38.37	0.75	0.03	0.62	0.03	1.35	2.03		1.35	1.67	
1	10-12	6c	0.88	62.73	36.38	0.67	0.03	0.58	0.03	1.35	1.81		1.35	1.56	
1	12-14	6c	0.71	33.06	66.23	0.15	0.01	0.08	0.01	1.35	0.41		1.35	0.21	
1	14-16	6c	0.63	59.02	40.35	0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
1	16-18	6c	4.14	34.03	61.83	0.20	0.02	0.11	0.02	1.35	0.54		1.35	0.30	
1	18-20	6c	1.71	56.91	41.38	0.03	0.01	0.03	0.01	1.35	0.09		1.35	0.07	
1	20-22	6c	1.87	56.25	41.89	0.10	0.01	0.08	0.01	1.35	0.27		1.35	0.21	
1	22-24	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
1	24-26	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
1	26-28	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
1	28-30	6c								1.35			1.35		
1	30-32	6c								1.35			1.35		
1	32-34	6c								1.35			1.35		
1	34-36	6c								1.35			1.35		
1	36-38	6c								1.35			1.35		
1	38-40	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00	12.94	1.35	0.00	10.59
2-1	0-20	6c	32.65	57.58	9.88	0.10	0.01	0.32	0.51	1.35	2.62		1.35	8.78	
2-1	20-40	6c	11.82	80.72	7.46	0.03	0.01	0.10	0.01	1.35	0.87		1.35	2.64	
2-1	40-44	6c	14.41	72.66	12.92	0.10	0.01	0.21	0.01	1.35	0.52		1.35	1.16	
Δ2-1										1.35	0.59		1.35	1.31	
Δ2-1										1.35	0.82		1.35	2.63	
2-1	53-59	RC	14.09	78.95	6.96	0.13	0.01	0.43	0.02	1.35	1.09		1.35	3.51	
2-1	59-63	RC				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
2-1	63-68	RC								1.35			1.35		

LEGEND

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Average bulk density calculated from porosity

Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g) Raw		Grain-normalized		Cesium Inventories (dpm/cm2) Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
Δ2-1										1.35	0.00		1.35	0.00	
Δ2-1										1.35	0.00		1.35	0.00	
2-1	70-80	A	12.44	80.00	7.56	0.12	0.01	0.35	0.01	1.35	1.58		1.35	4.79	
2-1	80-83	A	21.29	71.20	7.51	0.06	0.01	0.20	0.01	1.35	0.24		1.35	0.80	
2-1	83-93	A	5.66	92.85	1.49	0.08	0.01	0.41	0.01	1.35	1.09	**9.42**	1.35	5.53	**31.14**
2-2	0-20	6c	16.81	73.54	9.65	0.35	0.02	0.97	0.03	1.35	9.49		1.35	26.19	
2-2	20-40	6c	7.92	86.12	5.96	0.13	0.01	0.41	0.02	1.35	3.39		1.35	11.04	
2-2	40-41	6c	2.10	76.07	21.83	0.10	0.01	0.13	0.01	1.35	0.14	**13.02**	1.35	0.18	**37.41**
2-3	0-20	6c	8.44	72.79	18.77	0.12	0.01	0.20	0.01	1.35	3.35		1.35	5.32	
2-3	20-40	6c	17.66	75.80	6.54	0.07	0.01	0.24	0.01	1.35	1.88		1.35	6.53	
2-3	40-42	6c	38.42	46.55	15.03	0.06	0.01	0.17	0.01	1.35	0.16	**5.40**	1.35	0.45	**12.30**
2-4	0-20	6c	11.16	67.25	21.59	0.16	0.01	0.24	0.02	1.35	4.37		1.35	6.42	
2-4	20-39	6c	8.33	84.88	6.79	0.11	0.01	0.33	0.01	1.35	2.74		1.35	8.40	
2-4	39-41	6c	5.84	79.29	14.88	0.17	0.01	0.31	0.02	1.35	0.46	**7.57**	1.35	0.83	**15.64**
3	*note 158	6c	23.29	71.63	5.08	0.10	0.01	0.43	0.02	1.35	0.00	**na**	1.35	0.00	**na**
4-1	0-20		0.94	64.78	34.27	0.31	0.02	0.28	0.02	1.35	8.35		1.35	7.53	
4-1	20-40		0.58	55.87	43.54	0.42	0.02	0.31	0.02	1.35	11.30		1.35	8.26	
4-1	40-42		1.13	64.69	34.18	0.03	0.01	0.03	0.01	1.35	0.09		1.35	0.08	
Δ4-1								0.0000	0.0000	1.35	0.18		1.35	0.16	
Δ4-1								0.0000	0.0000	1.35	0.00		1.35	0.00	
4-1	50-68	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
4-1	68-80	A								1.35			1.35		
4-1	80-94	A								1.35			1.35		
4-1	94-108	A								1.35			1.35		
4-1	108-123	A								1.35			1.35		
4-1	123-137	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00	**19.91**	1.35	0.00	**16.04**
4-2	0-20	6c	1.66	68.15	30.19	0.29	0.01	0.30	0.01	1.35	7.95		1.35	8.05	
note 4-2	20-30									1.35	0.00		1.35	0.00	
4-2	30-37	6c	0.66	68.23	31.11	0.41	0.02	0.40	0.02	1.35	3.83		1.35	3.74	

LEGEND

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Average bulk density calculated from porosity

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
4-2	37-39	6c	0.29	30.31	69.40	0.32	0.02	0.16	0.02	1.35	0.88		1.35	0.42	
Δ4-2										1.35	2.20		1.35	1.05	
Δ4-2										1.35	0.00		1.35	0.00	
4-2	49-64	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
4-2	64-77	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
4-2	77-95	A								1.35			1.35		
4-2	95-116	A								1.35			1.35		
4-2	116-131	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00	**14.86**	1.35	0.00	**13.26**
4-3	0-20	6c	2.59	92.80	4.61	0.14	0.01	0.50	0.02	1.35	3.88		1.35	13.47	
4-3	20-38	6c	1.68	64.30	34.02	0.44	0.02	0.40	0.02	1.35	10.64		1.35	9.73	
4-3	38-40	6c	22.39	66.13	11.49	0.05	0.01	0.13	0.01	1.35	0.13		1.35	0.36	
note 4-3	36-51	A	0.36	60.29	39.35	0.29	0.02	0.23	0.02	1.35	4.36		1.35	3.48	
4-3	51-70	A	0.18	46.72	53.10	0.35	0.02	0.21	0.02	1.35	9.02		1.35	5.51	
4-3	70-81	A	0.31	49.46	50.23	0.08	0.01	0.05	0.01	1.35	1.15		1.35	0.74	
4-3	81-95	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
4-3	95-107	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
4-3	107-122	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00	**29.20**	1.35	0.00	**33.29**
5	*note 0	na	2.77	81.48	15.75	0.14	0.01	0.24	0.01	1.35	0.00	**na**	1.35	0.00	**na**
6plot	bag#1	na	87.43	10.16	2.41	0.0000	0.0000	0.20	0.0000	1.35	0.00		1.35	0.00	
6plot	bag#2	na								1.35			1.35		
6plot	bag#3	na								1.35			1.35		
6plot	bag#4	na								1.35			1.35		
6bank	bag#1	na	27.79	59.50	12.71	0.10	0.01	0.27	0.01	1.35	0.00		1.35	0.00	
b6	bag#1	na	0.00	67.00	33.00	0.13	0.01	0.12	0.01	1.35	0.00		1.35	0.00	
b6	bag#2	na								1.35		**na**	1.35		**na**
7	0-20	6c	1.31	71.59	27.09	0.38	0.02	0.42	0.02	1.35	10.27		1.35	11.32	
7	20-35	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
7	35-37	6c				0.0000	0.0000			1.35	0.00		1.35	0.00	
Δ7										1.35	0.00		1.35	0.00	

LEGEND

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Average bulk density calculated from porosity

Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
Δ7										1.35	0.00		1.35	0.00	
7	40-60	A				0.0000	0.0000			1.35	0.00		1.35	0.00	
7	60-77	A				0.0000	0.0000			1.35	0.00		1.35	0.00	
7	77-85	A				0.0000	0.0000			1.35	0.00		1.35	0.00	
7	85-96	A								1.35			1.35		
7	96-103	A								1.35			1.35		
7	103-113	A								1.35			1.35		
7	113-124	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00	**10.27**	1.35	0.00	**11.32**
8	0-2	6c	2.62	45.96	51.42	0.47	0.02	0.30	0.02	1.35	1.26		1.35	0.81	
8	2-4	6c	2.48	73.78	23.74	0.45	0.02	0.56	0.03	1.35	1.21		1.35	1.51	
8	4-6	6c	2.91	45.73	51.36	0.46	0.02	0.30	0.02	1.35	1.25		1.35	0.81	
8	6-8	6c	2.12	63.78	34.10	0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	8-10	6c	2.28	62.99	34.73	0.45	0.02	0.40	0.02	1.35	1.21		1.35	1.09	
8	10-12	6c				0.21	0.01			1.35			1.35		
8	12-14	6c	3.19	41.50	55.30	0.05	0.01	0.03	0.01	1.35	0.15		1.35	0.09	
8	14-16	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	16-18	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	18-20	6c								1.35			1.35		
8	20-22	6c								1.35			1.35		
8	22-24	6c								1.35			1.35		
8	24-26	6c								1.35			1.35		
8	26-28	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	28-30	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	30-32	6c								1.35			1.35		
8	32-34	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	34-36	6c				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	36-38	6c								1.35			1.35		
8	38-40	6c								1.35			1.35		
8	40-42	6c								1.35			1.35		

LEGEND

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
Δ8										1.35	0.00		1.35	0.00	
Δ8										1.35	0.00		1.35	0.00	
8	45-62	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
8	62-73	A								1.35			1.35		
8	73-80	A								1.35			1.35		
8	80-93	A								1.35			1.35		
8	93-104	A								1.35			1.35		
8	104-115	A								1.35			1.35		
8	115-128	A								1.35			1.35		
8	128-139	A				0.0000	0.0000	0.0000	0.0000	1.35	0.00	**5.08**	1.35	0.00	**4.31**
9	0-2		13.66	72.61	13.73	1.05	0.02	2.21	0.03	1.35	2.83		1.35	5.98	
9	2-4		10.41	76.13	13.46	1.03	0.03	2.13	0.04	1.35	2.79		1.35	5.75	
9	4-6		9.74	75.08	15.18	0.43	0.02	0.80	0.03	1.35	1.15		1.35	2.16	
9	6-8		9.79	76.44	13.76	0.22	0.01	0.44	0.02	1.35	0.59		1.35	1.20	
9	8-10		11.37	73.83	14.80	0.12	0.01	0.23	0.01	1.35	0.32		1.35	0.62	
9	10-20					0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
9	20-30									1.35			1.35		
9	30-32									1.35		**7.69**	1.35		**15.71**
10	0-2		19.53	70.60	9.87	0.65	0.02	1.82	0.03	1.35	1.75		1.35	4.93	
10	2-4		16.64	69.69	13.67	0.82	0.02	1.80	0.03	1.35	2.22		1.35	4.86	
10	4-6		16.02	69.96	14.02	1.03	0.03	2.20	0.04	1.35	2.78		1.35	5.95	
10	6-8		17.52	56.53	25.96	0.91	0.03	1.25	0.03	1.35	2.47		1.35	3.37	
10	8-10		18.57	61.97	19.46	0.79	0.02	1.37	0.03	1.35	2.13		1.35	3.69	
10	10-20		14.35	70.17	15.48	0.38	0.02	0.74	0.02	1.35	5.09		1.35	9.94	
10	20-30		9.73	62.90	27.38	0.14	0.01	0.17	0.01	1.35	1.92		1.35	2.29	
10	30-32		7.17	55.17	37.66	0.0000	0.0000	0.0000	0.0000	1.35	0.00	**18.36**	1.35	0.00	**35.04**

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g) Raw		Grain-normalized		Cesium Inventories (dpm/cm2) Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
BANGLADESH: 11-94															
o.meghna	30-40	A								1.35			1.35		
m.meghna	30-40	A								1.35			1.35		
m.meghna	50-60	A								1.35		na	1.35		na
11	0-10	H	0.84	77.25	21.91	0.15	0.01	0.20	0.01	1.35	0.00		1.35	0.00	
Δ11										1.35	0.00		1.35	0.00	
Δ11										1.35	0.00		1.35	0.00	
11	20-30	VC	7.87	70.94	21.19	0.17	0.01	0.24	0.02	1.35	0.00		1.35	0.00	
Δ11										1.35	0.00		1.35	0.00	
Δ11										1.35	0.00		1.35	0.00	
11	120-130	VC	1.88	74.28	23.84	0.18	0.01	0.22	0.02	1.35	0.00	0.00	1.35	0.00	0.00
12	0-15	VC	4.36	70.30	25.34	0.18	0.01	0.21	0.02	1.35	0.00		1.35	0.00	
12	15-30	VC	6.60	83.88	9.53	0.09	0.01	0.22	0.01	1.35	0.00		1.35	0.00	
12	30-45	VC	3.40	54.97	41.64	0.47	0.02	0.37	0.02	1.35	0.00		1.35	0.00	
12	45-60	VC	5.47	54.26	40.27	0.29	0.01	0.23	0.02	1.35	0.00		1.35	0.00	
12	60-65	VC				0.0000	0.0000			1.35	0.00	0.00	1.35		0.00
13	0-10	VC	1.72	59.86	38.43	0.30	0.02	0.25	0.02	1.35	0.00		1.35	0.00	
13	10-20	H	0.58	75.76	23.66	0.27	0.02	0.33	0.02	1.35	0.00		1.35	0.00	
Δ13										1.35	0.00		1.35	0.00	
Δ13										1.35	0.00		1.35	0.00	
13	130-140	VC				0.0000	0.0000			1.35	0.00	0.00	1.35	0.00	0.00
14	0-10	H	5.79	37.40	56.81	0.36	0.02	0.22	0.02	1.35	0.00		1.35	0.00	
Δ14										1.35	0.00		1.35	0.00	
Δ14										1.35	0.00		1.35	0.00	
14	20-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
Δ14										1.35			1.35		
Δ14										1.35			1.35		
14	40-50	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
Δ14										1.35			1.35		

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Average bulk density calculated from porosity

Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
Δ14										1.35			1.35		
14	80-90	TC				na				1.35		**0.00**	1.35		**0.00**
15-1	0-15	TC	1.89	59.26	38.85	0.49	0.02	0.40	0.02	1.35	0.00		1.35	0.00	
15-1	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-1	30-45	TC				na				1.35			1.35		
15-1	45-60	TC				na				1.35			1.35		
15-1	60-64	TC				na				1.35		**9.89**	1.35		**0.00**
15-2	0-15	TC	1.12	42.71	56.16	0.74	0.03	0.44	0.03	1.35	0.00		1.35	0.00	
15-2	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-2	30-45	TC				na				1.35			1.35		
15-2	45-60	TC				na				1.35			1.35		
15-2	60-64	H				na				1.35		**15.08**	1.35		**0.00**
15-3	0-15	TC	6.90	59.86	33.24	0.52	0.02	0.51	0.03	1.35	0.00		1.35	0.00	
15-3	15-30	TC	10.50	13.19	76.31	0.11	0.01	0.05	0.01	1.35	0.00		1.35	0.00	
15-3	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-3	45-60	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-3	60-75	TC				na				1.35			1.35		
15-3	75-90	TC				na				1.35			1.35		
15-3	90-105	TC				na				1.35			1.35		
15-3	105-115?	A				na				1.35			1.35		
Δ15-3										1.35			1.35		
Δ15-3										1.35			1.35		
15-3	180-190	A				na				1.35		**0.00**	1.35		**0.00**
15-4	0-15	TC	1.47	26.90	71.63	0.74	0.03	0.35	0.02	1.35	0.00		1.35	0.00	
15-4	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-4	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-4	45-60	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-4	60-65	H				na				1.35			1.35		
Δ15-4										1.35			1.35		

LEGEND

Sampler
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A: auger
CS: core sample (ring?)

Texture
L: loam
Sa: sand, sandy
Si: silt, silty
C: clay
F: fine

Note:
Δ indicates interpolated activity

Average bulk density calculated from porosity

Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
Δ15-4										1.35			1.35		
15-4	100-110	A				na				1.35		**14.95**	1.35		0.00
15-5	0-18	TC	3.73	88.28	7.99	0.10	0.01	0.26	0.01	1.35	0.00		1.35	0.00	
15-5	18-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-5	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-5	45-60	TC				na				1.35			1.35		
15-5	60-72	TC				na				1.35			1.35		
15-5	72-95	TC				na				1.35			1.35		
15-5	95-102	TC				na				1.35			1.35		
15-5	102-120	TC				na				1.35			1.35		
Δ15-5										1.35			1.35		
Δ15-5										1.35			1.35		
15-5	228-238	A				na				1.35		**2.41**	1.35		0.00
15-6	0-15	TC	11.21	65.61	23.17	0.39	0.02	0.54	0.02	1.35	0.00		1.35	0.00	
15-6	15-30	TC	12.49	69.83	17.68	0.07	0.01	0.12	0.01	1.35	0.00		1.35	0.00	
15-6	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-6	45-60	TC				na				1.35			1.35		
15-6	60-65	H				na				1.35		**0.00**	1.35		0.00
15-7	0-15	TC	2.51	42.80	54.69	0.61	0.03	0.37	0.03	1.35	0.00		1.35	0.00	
15-7	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-7	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
15-7	45-60	TC				na				1.35			1.35		
15-7	60-65	H				na				1.35			1.35		
Δ15-7										1.35			1.35		
Δ15-7										1.35			1.35		
15-7	175-185	A				na				1.35		**12.31**	1.35		0.00
16	0-10	TC	4.06	44.80	51.14	0.65	0.03	0.43	0.03	1.35	0.00		1.35	0.00	
16	10-20	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
16	20-30	TC				na				1.35			1.35		

LEGEND

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Δ indicates interpolated activity

Average bulk density calculated from porosity

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
16	30-45	TC				na				1.35			1.35		
16	45-60	TC				na				1.35			1.35		
16	60-65	H								1.35			1.35		
Δ16										1.35			1.35		
Δ16										1.35			1.35		
16	110-120	A								1.35		**8.76**	1.35		**0.00**
17	0-15	TC	15.80	53.38	30.82	0.56	0.02	0.65	0.03	1.35	0.00		1.35	0.00	
17	15-30	TC	15.84	52.10	32.07	0.64	0.03	0.71	0.03	1.35	0.00		1.35	0.00	
17	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
17	45-60	TC				na				1.35			1.35		
17	60-65	H				na				1.35			1.35		
Δ17										1.35			1.35		
Δ17										1.35			1.35		
17	115-125	A				na				1.35		**0.00**	1.35		**0.00**
18	0-15	TC	12.36	63.19	24.45	0.37	0.02	0.50	0.03	1.35	0.00		1.35	0.00	
18	15-30	TC	8.99	57.33	33.67	0.22	0.02	0.22	0.02	1.35	0.00		1.35	0.00	
18	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
18	45-60	TC				na				1.35			1.35		
18	60-65	H				na				1.35			1.35		
Δ18										1.35			1.35		
Δ18										1.35			1.35		
18	160-170	A				na				1.35		**0.00**	1.35		**0.00**
19	0-15	TC	3.40	42.50	54.10	0.70	0.03	0.43	0.03	1.35	0.00		1.35	0.00	
19	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
19	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
19	45-60	TC				na				1.35			1.35		
19	60-65	H				na				1.35			1.35		
Δ19										1.35			1.35		
Δ19										1.35			1.35		

LEGEND

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Si: silt, silty
C: clay
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Δ indicates interpolated activity

Average bulk density calculated from porosity

Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
19	125-135	A				na				1.35		14.15	1.35		0.00
20	0-15	TC	8.16	54.37	37.47	0.68	0.03	0.61	0.03	1.35	0.00		1.35	0.00	
20	15-30	TC	6.21	51.21	42.58	0.05	0.01	0.04	0.01	1.35	0.00		1.35	0.00	
20	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
20	45-60	TC				na				1.35			1.35		
20	60-65	H				na				1.35		0.00	1.35		0.00
21-1	0-15	TC	8.42	25.19	66.40	0.54	0.03	0.29	0.03	1.35	0.00		1.35	0.00	
21-1	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
21-1	30-45	TC				na				1.35			1.35		
21-1	45-60	TC				na				1.35			1.35		
21-1	60-65	H				na				1.35		10.90	1.35		0.00
21-2	0-15	TC	3.68	50.09	46.23	0.48	0.02	0.34	0.02	1.35	0.00		1.35	0.00	
21-2	15-30	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
21-2	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
21-2	45-60	TC				na				1.35			1.35		
21-2	60-65	H				na				1.35		9.67	1.35		0.00
22	0-15	TC	4.03	62.09	33.38	0.61	0.02	0.58	0.03	1.35	0.00		1.35	0.00	
22	15-30	TC	1.24	70.71	28.05	0.07	0.01	0.07	0.01	1.35	0.00		1.35	0.00	
22	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
22	45-60	TC				na				1.35			1.35		
22	60-65	H				na				1.35			1.35		
Δ22										1.35			1.35		
Δ22										1.35			1.35		
22	120-130	A				na				1.35		0.00	1.35		0.00
23-1	0-5	H	24.14	58.49	17.37	0.0000	0.0000	0.0000	0.0000	1.35	0.00		1.35	0.00	
Δ23-1										1.35	0.00		1.35	0.00	
Δ23-1										1.35	0.00		1.35	0.00	
23-1	15-20	H	5.49	65.87	28.64	0.16	0.01	0.17	0.02	1.35	0.00		1.35	0.00	
Δ23-1										1.35	0.00		1.35	0.00	

LEGEND

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g)				Cesium Inventories (dpm/cm2)					
						Raw		Grain-normalized		Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
Δ23-1										1.35			1.35		
23-1	35-40	C				0.0000	0.0000			1.35	0.00		1.35	0.00	
Δ23-1										1.35			1.35		
Δ23-1										1.35			1.35		
23-1	175-185	A				na				1.35		**0.00**	1.35		**0.00**
23-2	0-15	TC	0.24	55.37	44.39	0.45	0.02	0.32	0.02	1.35	0.00		1.35	0.00	
23-2	15-30	TC	0.06	52.87	47.07	0.17	0.01	0.11	0.02	1.35	0.00		1.35	0.00	
23-2	30-45	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
23-2	45-60	TC				na				1.35			1.35		
Δ23-2										1.35			1.35		
Δ23-2										1.35			1.35		
23-2	90-100	A				na				1.35			1.35		
Δ23-2										1.35			1.35		
Δ23-2										1.35			1.35		
23-2	165-175	A				na				1.35		**0.00**	1.35		**0.00**
24	0-10	TC	4.81	53.02	42.17	0.71	0.02	0.56	0.03	1.35	0.00		1.35	0.00	
24	10-20	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
24	20-35	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
24	35-50	TC				na				1.35			1.35		
24	60-65	H				na				1.35			1.35		
Δ24										1.35			1.35		
Δ24										1.35			1.35		
24	120-130	A				na				1.35		**9.61**	1.35		**0.00**
25	0-10	TC	16.49	53.45	30.06	0.55	0.03	0.65	0.03	1.35	0.00		1.35	0.00	
25	10-18	TC	10.14	53.56	36.30	0.34	0.02	0.32	0.02	1.35	0.00		1.35	0.00	
25	18-35	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
25	35-50	TC				na				1.35			1.35		
Δ25										1.35			1.35		
Δ25										1.35			1.35		

LEGEND

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Δ indicates interpolated activity

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Table IV.8 Results of Cesium Analysis (cont.)

			Grain Size Analysis			Cesium Activity (dpm/g) Raw		Grain-normalized		Cesium Inventories (dpm/cm2) Raw Activity			Normalized Activity		
Site	Depth (cm)	Sampler	% sand	% silt	% clay	Activity	Error	Activity	Error	B.d. (g/cc)	Subtotal	TOTAL	B.d. (g/cc)	Subtotal	TOTAL
25	60-65	H				na				1.35		**0.00**	1.35		0.00
26	0-12	TC	0.73	54.30	44.97	0.71	0.03	0.50	0.03	1.35	0.00		1.35	0.00	
26	12-23	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
26	23-36	TC				0.0000	0.0000			1.35	0.00		1.35	0.00	
26	36-51	TC				na				1.35			1.35		
26	51-60	TC				na				1.35		**11.48**	1.35		0.00
27	0-10	H	22.18	54.63	23.19	0.53	0.02	0.84	0.03	1.35	0.00		1.35	0.00	
27	10-20	H	17.23	51.40	31.37	0.23	0.02	0.26	0.02	1.35	0.00		1.35	0.00	
27	20-30	H	22.96	44.76	32.28	0.15	0.01	0.18	0.02	1.35	0.00		1.35	0.00	
27	30-40	H				0.0000	0.0000			1.35	0.00	**0.00**	1.35	0.00	0.00
28	0-11	TC	3.81	42.42	53.77	0.92	0.03	0.58	0.03	1.35	0.00		1.35	0.00	
28	11-20	TC	0.97	41.00	58.03	0.69	0.02	0.39	0.02	1.35	0.00		1.35	0.00	
28	20-35	TC	0.06	38.08	61.86	0.0000	0.0000		0.0000	1.35	0.00		1.35	0.00	
28	35-50	TC	0.27	62.33	37.40	0.24	0.01	0.20	0.01	1.35	0.00		1.35	0.00	
Δ28										1.35	0.00		1.35	0.00	
Δ28										1.35			1.35		
28	60-65	H				na				1.35		**0.00**	1.35		0.00

LEGEND

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Appendix V

THE USE OF SEDIMENT BALANCE TO ESTIMATE FLOODPLAIN SEDIMENTATION

1 Introduction

The balance of suspended sediments in a defined fluvial system can be determined if the sediment inputs and outputs to that system are quantified at its boundaries. The balance indicates the gross sedimentary behavior of the entire system. Determinations of sediment balance usually are made on a mean annual basis, and the results indicate the total aggradation or degradation of the system. This appendix uses BWDB suspended sediment data to examine the sediment balance in a defined fluvial system (Figure V.1) consisting of the Jamuna, Ganges, and Padma rivers. Section 2 describes this fluvial system in greater detail.

Sediment sampling along the rivers of what is now Bangladesh began in 1957 (MPO 1987a) under the precursor agency to the Bangladesh Water Development Board (BWDB). In 1965, the FAO (1969) began systematizing water data collection efforts. Today, as a result, Bangladesh has about 300 water level stations and 80 discharge measurement stations, 25 of which make sedimentation measurements (BWDB 1972, BWDB 1982). MPO reported in 1987 that suspended sediment concentration information was available for about 51 stations prior to 1983 (excluding 1971, when data gathering was suspended due to the Liberation War). Since 1969 these data have been extensively used by researchers and consultancy organizations.

2 The Fluvial System

The defined fluvial system examined in this report comprises three major rivers, the Jamuna, Ganges, and Padma. The system analyzed in this report also includes the Dhaleswari River, a distributary of the Jamuna, and the Gorai River, a distributary of the Ganges. The inflow boundaries are on the Brahmaputra River at Bahadurabad and on the Ganges River at Hardinge Bridge. The outflow boundaries are on the Padma River at Baruria (Mawa for the CBJET [1991] case), on the Gorai River at Kushtia, and on the Dhaleswari River at Jagir and Taraghat. Table V.1 summarizes estimates made of the mean annual suspended sediment transport of the three major rivers according to various sizes. The remainder of this section briefly describes the fluvial environment of the rivers in the system.

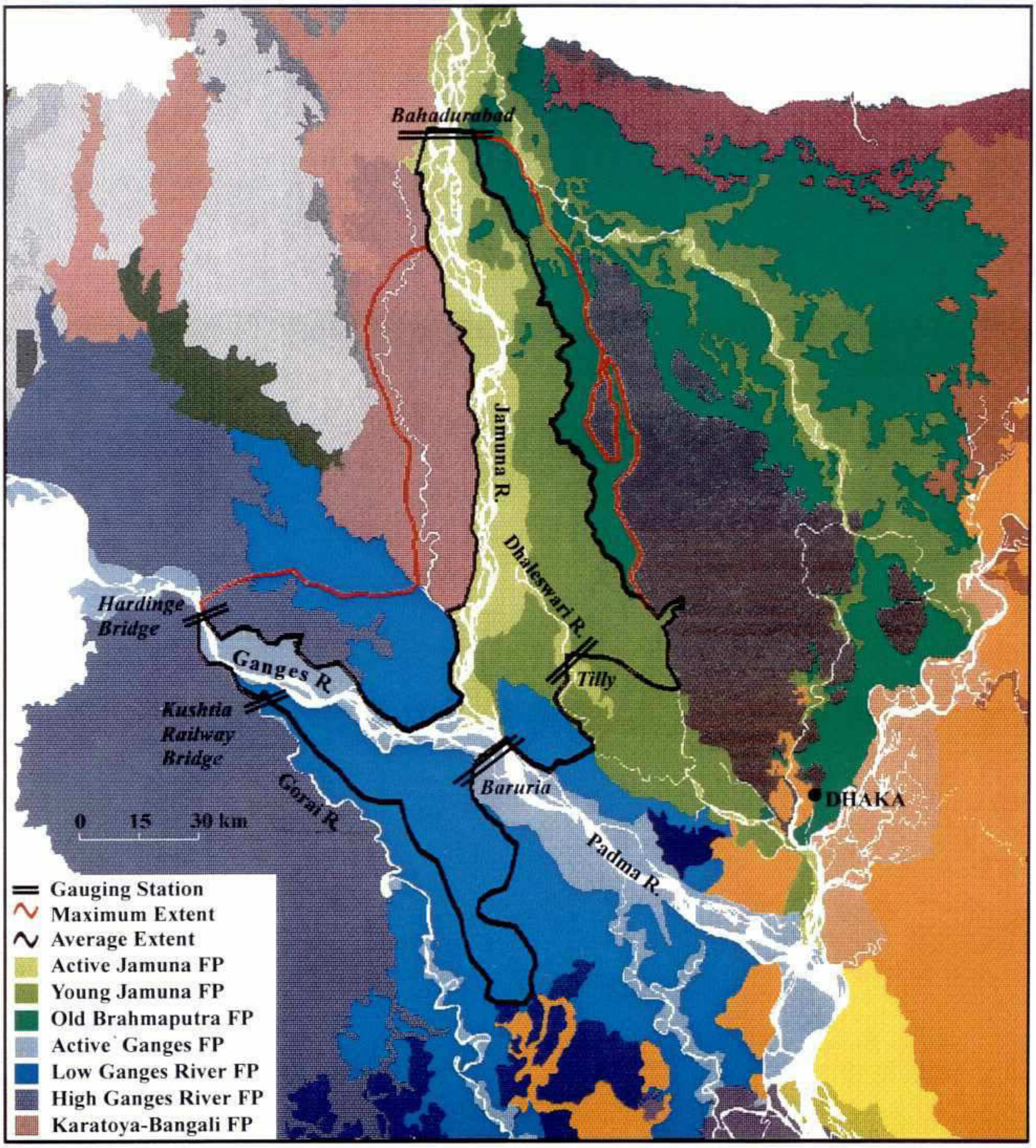
Table V.1 Mean Annual Suspended Sediment Transport of Rivers (million tons)

River	Coleman	CBJET	MPO	FEC	Hossain	RSP (FAP 24)	BWDB
Jamuna	608	499	387	431	650	586	500
Ganges	479	196	212	338	480	549	450
Padma		581	563			894	694

Note: The Jamuna River transport is estimated at Bahadurabad. The Ganges River transport is estimated at Hardinge Bridge. The Padma River transport is estimated at Baruria and Mawa.

The Brahamaputra-Jamuna River, with a catchment area of about 573,500 km^2 and a length of 2,900 km, drains the northern and eastern slopes of the Himalayas. It is a wide, braided river with wandering thalwegs. Its mean annual discharge is about 19,600 m^3/s. The present course of the Jamuna River is only about 200 years old. Of the three major rivers in Bangladesh, the Jamuna carries the highest sediment

Figure V .1: The Jamuna-Ganges-Padma Fluvial System and Associated Floodplain with Location of BWDB Gauging Stations



Note: Partial physiography legend is shown. For all units refer to Figure 2.1

load both in terms of quantity and caliber (Barua 1994). The river has a bed slope of 7×10^{-5} and a median bed material grain size of 0.22 mm. Based on River Survey Project (RSP) measurements made in June 1993 at Bahadurabad, Barua (1995) indicated that the median grain sizes of surface-water sediments varied between 0.012 and 0.026 mm. Estimates of the river's mean annual suspended sediment transport range from 387 million tons (MPO 1987a) to 650 million tons (Hossain 1992).

The Ganges River drains the southern slope of the Himalayas and the northern part of the central Indian plateau. It has a catchment of 1,090,000 km^2 and a length of about 2,200 km. It is a wide, meandering river with wandering thalwegs. The river has a bed slope of about 5×10^{-5} and carries an annual discharge of 11,000 m^3/s. The median grain size of the riverbed material is 0.12 mm. Estimates of suspended sediment transport by the river range from 196 million tons (CBJET 1991) to 549 million tons (RSP 1994).

The Padma is a 120-km-long river reach extending from the Ganges-Jamuna confluence at Aricha to the Padma-Meghna confluence north of Chandpur. The reach drains the combined discharge of the Ganges and the Brahmaputra. The Padma has a generally straight course at its upper end and a double-thread braided lower end. The mean annual discharge of the river is about 28,000 m^3/s. The Padma has a slope of 5×10^{-5} and a median bed-material size of 0.09 mm. Estimates of the Padma's mean annual suspended sediment transport range from 563 million tons (MPO 1987a) to 894 million tons (RSP 1994).

The Dhaleswari River is one of the major left-bank distributaries of the Jamuna River. The mean annual discharge of the river for the 1987 hydrological year was about 600 m^3/s, representing some 4 percent of the Jamuna's discharge. The Dhaleswari has a bed slope of about 4.5×10^{-5}, and the median grain size of its bed material, measured at Tilly, is about 0.24 mm.

The Gorai River is a right-bank distributary of the Ganges River. Its mean annual discharge is 1,400 m^3/s, representing about 13 percent of the Ganges River discharge. The Gorai offtake is about 16 km downstream of Hardinge Bridge. The river's average slope is about 4×10^{-5}. The median grain size of its bed material in the upper reaches is about 0.15 mm.

3 Sediment Transport Data

3.1 Data Collection

As mentioned in the introduction, BWDB suspended sediment data extend back to 1957.

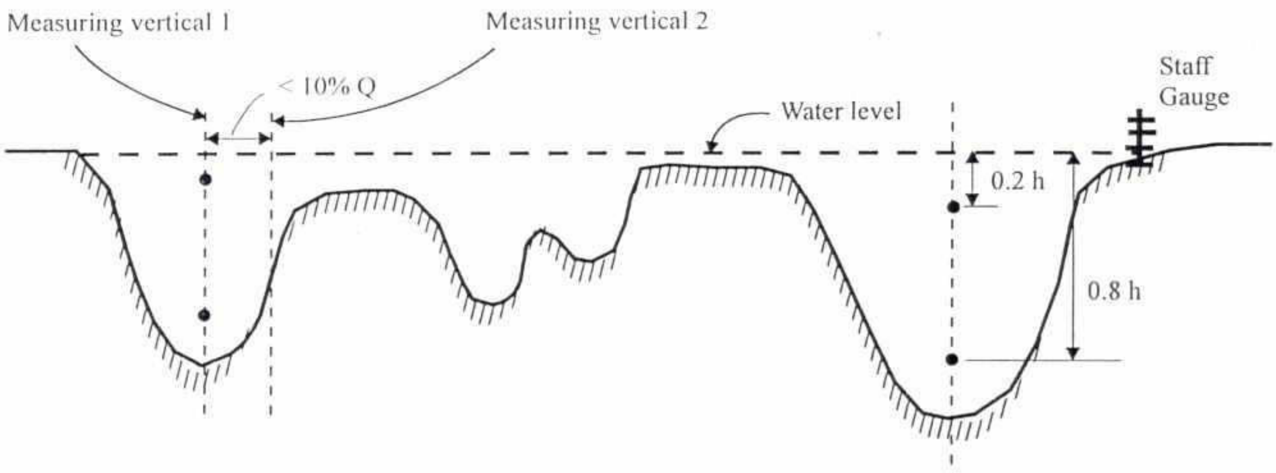


Figure V.2 River Cross-Section: BWDB Sediment Transport Measuring Schemes

BWDB collects these data using mooring vessels (Figure V.2) to periodically sample river transects: Using Brinkley instantaneous samplers, technicians collect water samples from two depths (20 percent and 80 percent) at several verticals along each transect. These verticals are chosen in such a way that discharge between two of them does not exceed 10 percent of the total discharge (WMO 1981). The sand and silt fractions of the samples are then separated from the water in the field. This is done by passing the sample through an elutriator for 100 seconds to separate the sand, which is collected in a tube. Silty water from alternate verticals is mixed and saved. The measurement process for each vertical usually takes several hours. The total sampling time for the Bahadurabad transect of the Jamuna River is usually about two days. The mean sand-concentration in each vertical is calculated by the Straub method (Indian Standard Institution 1969). Total discharge and suspended sediment transport through the transect is computed by the velocity-area method. Data usually are collected weekly during the monsoon period (May–November). At Bahadurabad, data are collected for the whole year.

The procedure described above has been in use since 1965. It should be noted, however, that RSP (1994) reported that some data are missing. Moreover, the quality of the available data has been questioned.

Halcrow (1992), using a one-dimensional morphological modelling exercise, demonstrated that discharge and sediment transport data for the period 1966–70 are consistent and reliable. Earlier, RPT-NEDECO-BCL (1989) and SWMC (1991) reached similar conclusions. The tested data were reported by the East Pakistan Water and Power Development Authority (EPWAPDA 1969). CBJET (1991), in its report, found large differences in Jamuna (Bahadurabad) sediment transport rating curves when comparing the period 1968–69 with 1980–82. More estimates occurred in the former years than in the latter.

3.2 Estimates of Annual Transport

To estimate annual sediment transport, daily transport data are needed. Since the BWDB data are for varying periods (some weekly), the "missing" data must be interpolated. This is generally done by developing Q-h and Q-Q_s relationships.

A Q-h relationship is a discharge rating curve between water level (h) and discharge (Q). Water levels (h) are observed five times daily, but discharges (Q) mostly are measured weekly. Once Q-h relationships have been established for a set of data, they can be used to estimate mean daily discharge (Q_s). From the established Q-h curves, mean daily discharge is read against mean daily water level.

A Q-Q_s relationship can then be similarly established from the data set. Using this relationship, mean daily Q_s (sediment transport rate) is estimated against mean daily Q. Most of the annual sediment transport estimates presented in Table V.1 were computed by this procedure.

Coleman (1969) did not explain how his monthly transport estimates were derived, but they probably were calculated by averaging available data. His data covered five years (1958–1962) that predated the 1965 establishment of the measuring technique now in use (FAO 1969). The MPO (1987a) estimates in Table V.1 were determined by establishing Q-Q_s relationships for measurements made between 1979 and 1983. Hossain's (1992) estimates are based on synthetic information derived from actual measurements and computed data using his equations (Hossain 1987). CBJET (1991) estimated transport by establishing Q-Q_s curves for several measured years. FEC (1989) used a different approach to make its estimates. First, it selected measured discharge and sediment transport with return periods of 50 dry years, 10 dry years, 2 dry years, 10 wet years, and 50 wet years. These data were then used to establish Q-Q_s relationships. The established relationships were used to estimate sediment transport at Bahadurabad and Hardinge Bridge from 1956 to 1988. The River Survey Project (RSP 1994) made a forced estimate of sediment transport for the years from 1966 to 1991 by using Q-Q_s relationships established with data from 1966 to 1970. The 1970 cut-off date was selected based on the argument that the data for later years are inconsistent.

4 Sediment Budget

Despite the limitations of existing data and analyses, they can be used to get an idea of the total sediment budget of the Jamuna-Ganges-Padma fluvial system. The completeness of the CBJET (1991) and RSP (1994) information make them particularly useful for this purpose.

Figure V.3 shows the annual suspended sediment transport for the period 1965–1988 based on the CBJET data. The data indicate that the import of suspended sediment ranges from 443 million tons in 1979 to 992 million tons in 1973, with a mean annual transport of about 695 million tons. Sediment export from the system ranges from 308 million tons in 1982 to 1,014 million tons in 1984, with a mean of about 581 million tons. Examination of the figure reveals that, in the 1965–70 period, import was consistently higher than export. In later years, however, import and export are inconsistent. Despite the inconsistency, the mean balance between import and export indicates that some 114 million tons remained within the fluvial system annually.

Analyses of FAP 24 River Survey Project (RSP 1994) data were used to prepare separate balances for silt/clay and sand fractions. Figure V.4 shows the silt and clay transport for the 1966–1991 period. Imports range from 556 million tons in 1972 to 908 million tons in 1988, with a mean of 740 million tons. Exports range from 416 million tons in 1972 to 774 million tons in 1988, with a mean of 571 million tons. These data are consistent. The balance shows a mean of 169 million tons of silt and clay remaining within the system annually.

Figure V.5 shows the sand transport for the 1966–1991 period. Imports range from 256 million tons in 1972 to 555 million tons in 1988, with a mean of about 398 million tons. Exports range from 211 million tons in 1972 to 703 million tons in 1988, with a mean of about 386 million tons. About 12 million tons of sand remained within the system.

To further confirm the data consistency, Figure V.6 shows silt/clay and sand suspended sediment transports. Figure V.7 summarizes the sediment transport balance, showing imports and exports through various river channels.

5 Floodplain Inundation

To show how sediment transport relates to flooding and floodplain sedimentation, annual hydrographs of the Serajganj transect were developed. These hydrographs indicate days when danger levels were exceeded. Danger level is defined as the average flood level with a return period of 2.33 years (FFWD 1993). This level is defined to provide people with warnings of floods that may damage crops and homesteads (FFWD 1993). Figure V.8 shows the number of days when floods exceeded this level at Serajganj. The figure shows a total period of nine years during which danger level is not reached. The estimates in Figures V.4 and V.5 are consistent with this flood information. The estimates in Figure V.3 are not consistent, however. Figures V.9a and V.9b present mean daily water level data for 1974 and 1988 and show where these exceed average flood level.

For analyzing and interpreting sediment budget estimates, the associated area within the fluvial system was defined using GIS mapping of physiograpy, river catchment boundaries, topography, and infrastructure. The challenge was in defining the boundaries of the floodplain area associated with the sediment transport estimates. As shown in Figure V.1, included was the portion of the Jamuna floodplain below the Bahadurabad measuring transect and above the Dhaleswari measuring station at Tilly. The affected Ganges floodplain included the areas below the measuring site at Hardinge Bridge, and excluded the Gorai floodplain, since sediments in this river floodplain were

Figure V.3 **Annual Suspended Sediment Transport for the Selected Fluvial System, 1965 - 1988**

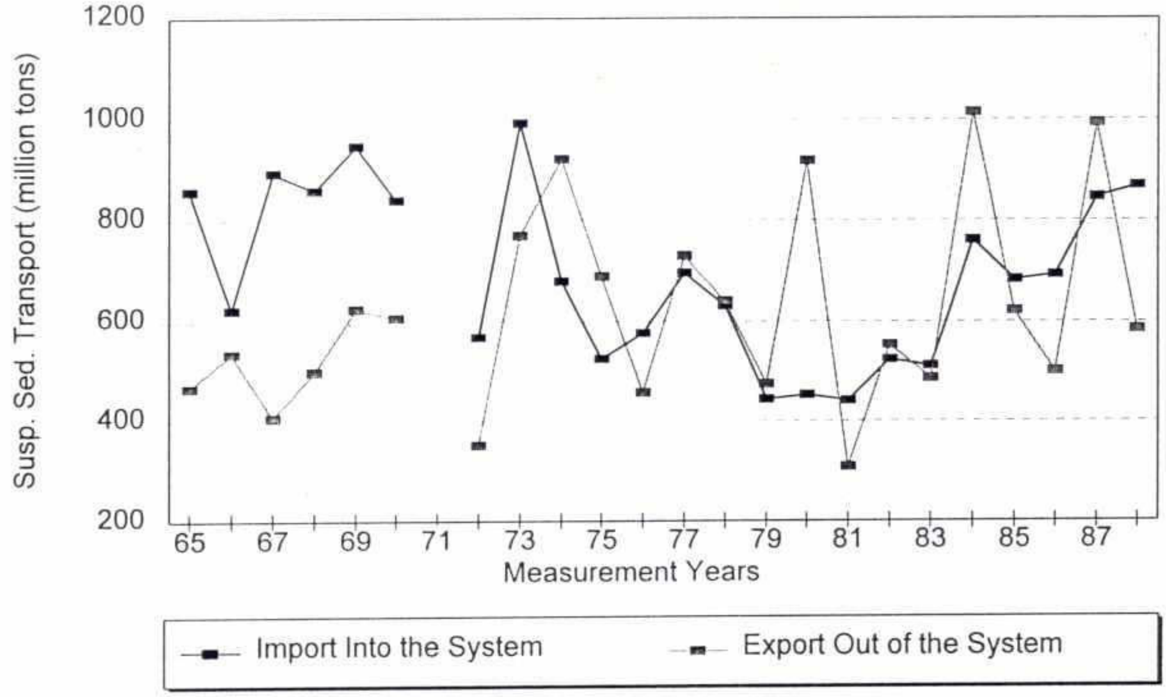


Figure V.4 **Annual Suspended Silt and Clay Transport for the Selected Fluvial System, 1966 - 1991**

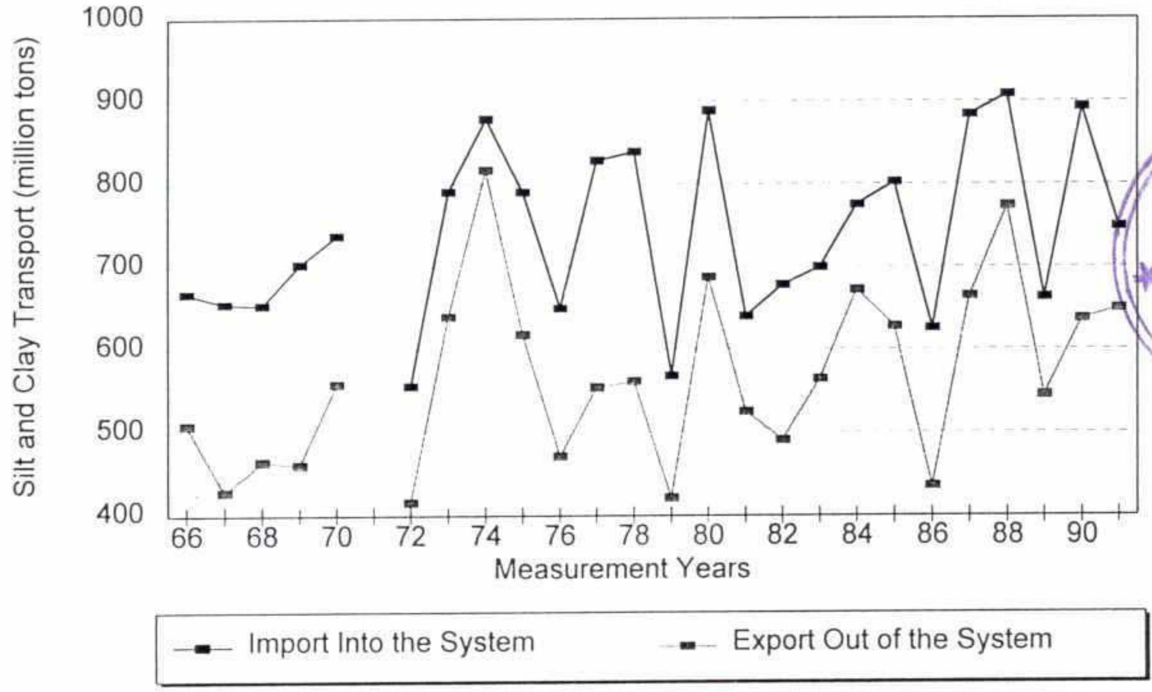


Figure V.5 Annual Suspended Sand Transport for the Selected Fluvial System, 1966 - 1991

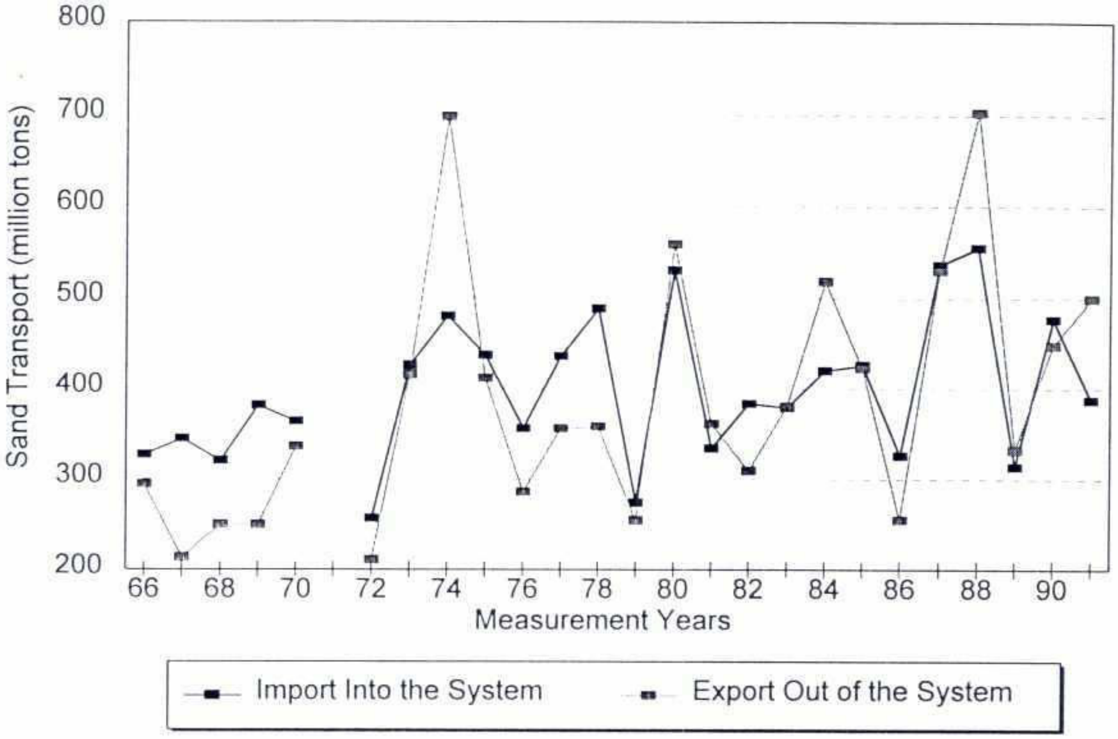
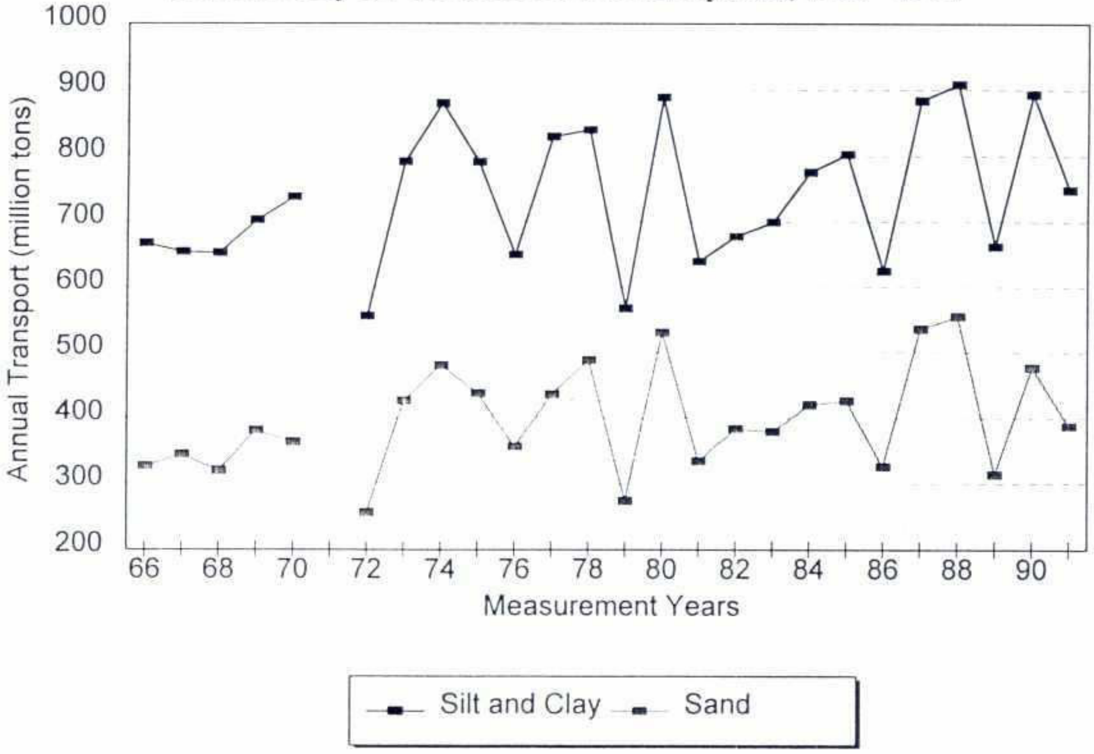


Figure V.6 Comparision of Imports of Suspended Sand With Imports of Suspended Silt and Clay for the Selected Fluvial System, 1966 - 1991



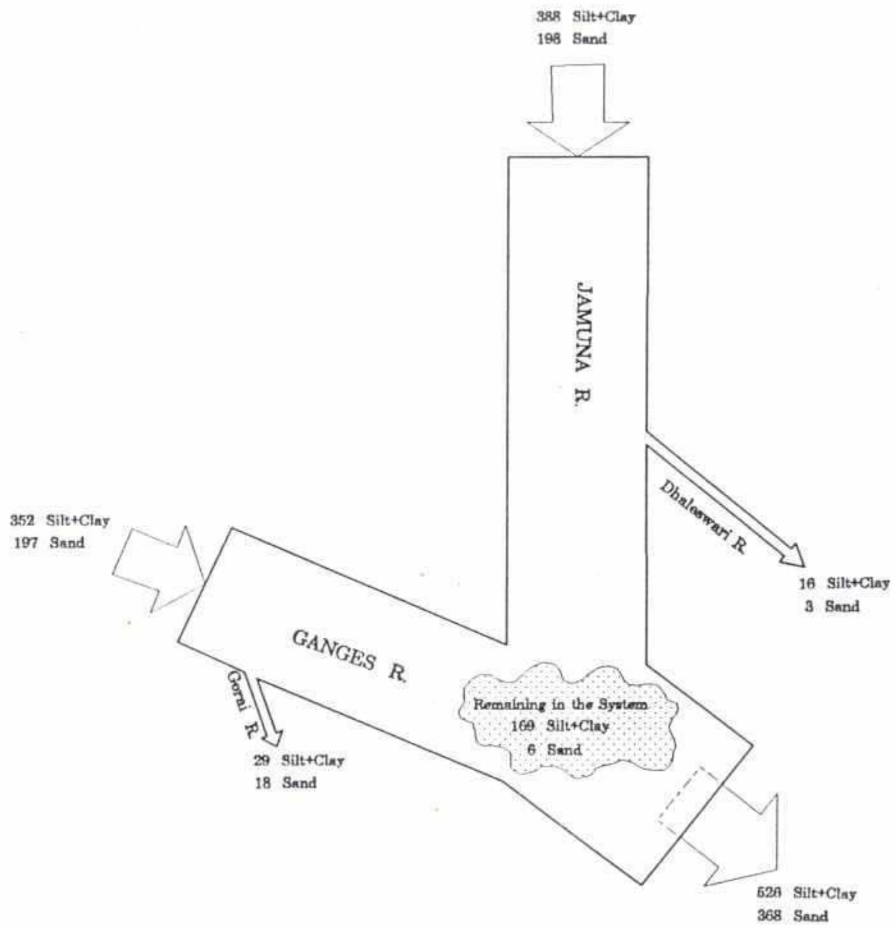


Figure V.7 Summary of Sediment Transport Balance

accounted for at the Kushtia Railway Bridge station. The lower end of the entire system was defined at Baruria station on the Padma, which measures the combined flow of the Ganges and the Jamuna rivers.

As shown in Figure V.1, the fluvial system occupies floodplains of three major regions—the northwest, southwest, and the north central. The two boundaries shown in the figure correspond with areas that are inundated under normal monsoon flooding conditions (inside boundary) and areas that are flooded in major flood events, such as the floods of 1987 and 1988. The floodplains of the northwest region are mostly isolated from the fluvial system by embankments (NWRS 1990) and floodwater from the Ganges and Jamuna rivers does not inundate much of this region. The north-central region is mainly inundated by the Padma River and the Brahmaputra-Jamuna and its distributaries, the Old Brahmaputra and Dhaleswari (NCRS 1993). In the southwest region, delineated is a portion of the lower Ganges floodplain. Also included is the active floodplain area of the three major rivers, about 2,770 km^2. The total area within the inner boundary, corresponding with normal flooding, is about 6,500 km^2. The outer boundary, which considers large flood events (which are likely major contributors to the total sediment deposited in the floodplain) in the northwest region and other areas, yields an estimate of about 10,148 km^2 of floodplain that is annually flooded.

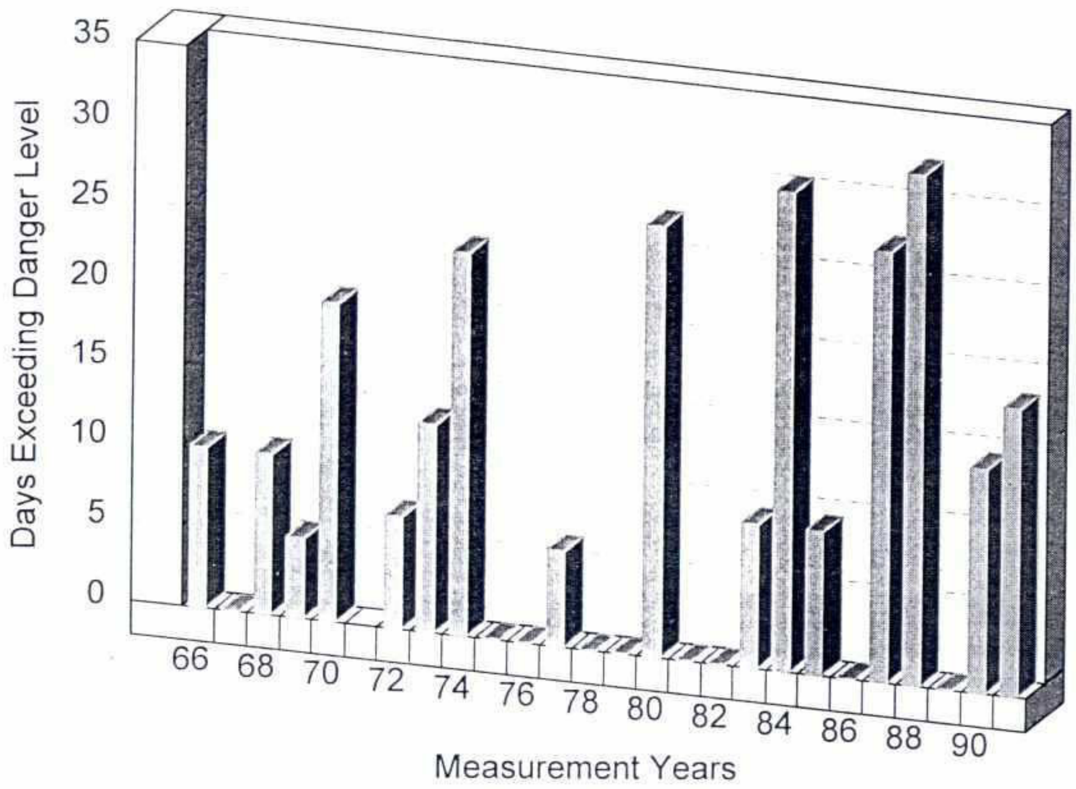


Figure V.8 Number of Days the Jamuna River Exceeded Danger Level at Serajganj, 1966–1991

6 Floodplain Sedimentation

Figures V.4 and V.5 show that the combined sand and silt fractions include some 175 million tons, or 15 percent of the total suspended sediment transport, which remains unaccounted for. Assuming a sediment bulk density of 1.5 g/cm^3, this represents 117 million m^3 of sediments. The 114 million tons estimated from CBJET data represents an amount of 76 million m^3. Assuming that the sediment measurements are accurate, then these unaccounted sediments must remain within the fluvial system. Their distribution among river channels and active floodplain areas is, in fact, not established. It is nonetheless useful to present the data, as in Table V.2, where a uniform distribution of the retained sediments over the floodplain is assumed. Using the 10,148 km^2 channel and floodplain area discussed in the above section, the average sedimentation rates are 7.5 mm/yr from CBJET sediment balance data, and 11.5 mm/yr from RSP data.

Table V.2 **Estimated Sedimentation Rates**

Floodplain area (km^2)	Sedimentation rate based on CBJET data (mm/year)	Sedimentation rate based on RSP data (mm/year)
10,148 (GIS-liberal)	7.5	11.5

Figure V.9a Example of the Hydrograph: Jamuna River at Sirajganj in 1974

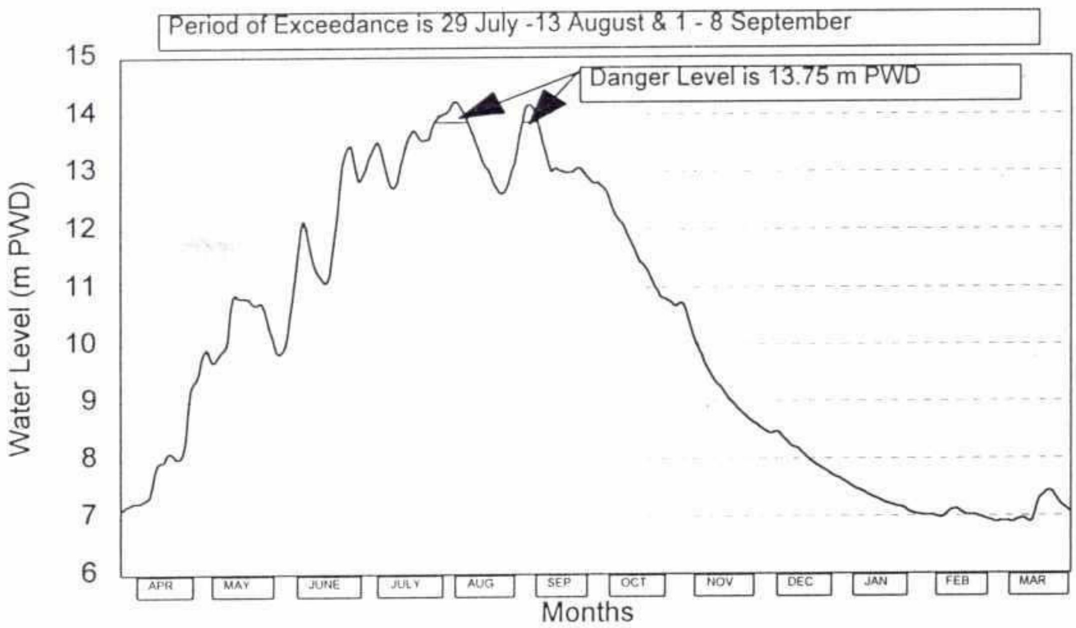
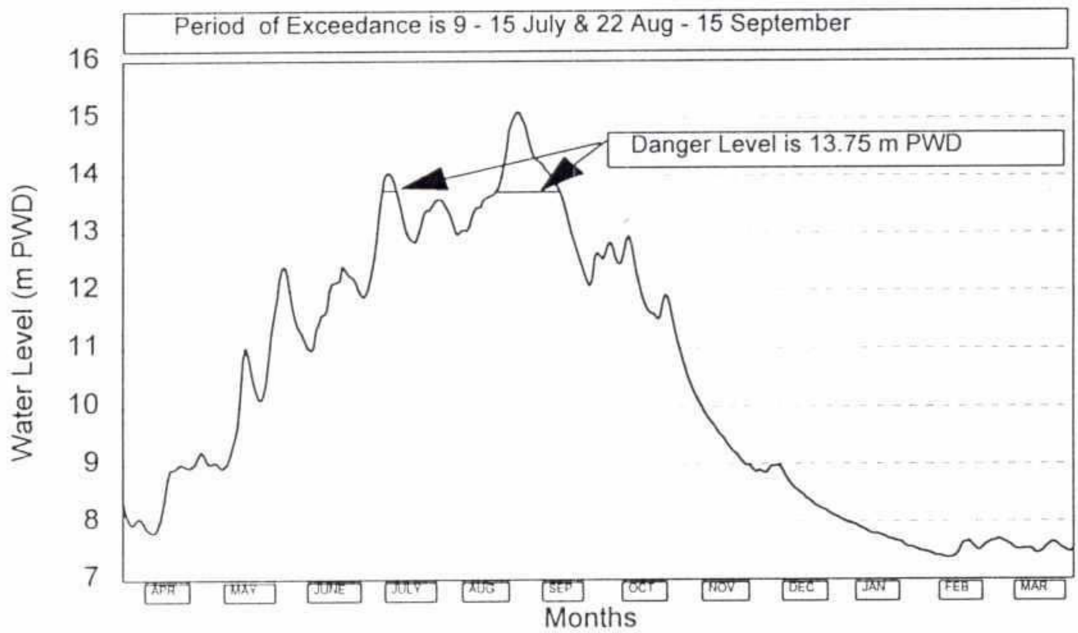


Figure V.9b Example of the Hydrograph: Jamuna River at Sirajganj in 1988



7 Discussion and Conclusions

Given an accounting of the sediment inputs and outputs of a fluvial system, this report demonstrates the possibility of using the sediment balance to make a gross estimate of floodplain sedimentation. However, both the data used and the analysis applied have limitations that should be borne in mind. This is particularly relevant in the considering the apparently high sedimentation rates obtained from such analyses.

Due to the difficulty of gauging sedimentation in a vast river network like the Jamuna-Ganges-Padma, the limited resources deployed to do so, and the significant amount of missing information, the estimates presented in this report must be considered general and indicative. First, it should be recognized that in the large and complicated river network of Bangladesh it is very difficult to locate a measurement transect in an ideal location such as prescribed by ISO (1977). There are always dangers of a transect being located in an overloaded or underloaded sedimentary environment. In the former case an overestimation can be made, while an underestimation can happen in the latter case. Studies by the Surface Water Modeling Center indicate that an overestimation of sediment transport can happen in places like Hardinge Bridge (Galappatti, 1993). Second, it should be noted that total sediment load consists of both suspended load and bed load. But the present analyses is based on suspended sediment only. It has been demonstrated by Yuqian (1993) that sediment balance considering only suspended load could not explain the morphological behavior of a reach of the large, braided Yellow River in China. Third, the suspended sediment sampling was made by an instantaneous Brikley sampler, which can have an inaccuarcy as high as 100 percent (Van Rijn, 1986). In addition, investigators have serious concerns about the use of sediment rating curves. Establishment of Q-Q_s relations is a practical approach that lacks a theoretical basis. Colby (1964), Nordin (1964), and Glysson (1987) cautioned against the use of such relations.

Another consideration is the difficulty of determining floodplain area. The considered period of about 25 years represents floods ranging from some extremely high floods, such as that of 1988, to some years with very low floods. Although the floodplain boundaries delineated in this study are considered reasonable, detailed inundation information for these years is unavailable.

Limitations aside, the estimates based on sediment balance indicate that some 15 percent of the total sediment load of the Ganges-Brahmaputra is sequestered in the fluvial system. This represents annual average sedimentation rates ranging from 7.5 to 11.5 mm/year. The lower sedimentation rate, which is based on the CBJET sediment balance data, compares favorably with the GIS model estimates of 8.1 mm/year. Since the floodplain area used in these calculations also includes active riverbeds, the sequestering of sediments within the fluvial system indicates a net aggradation of the riverbed. Aggradation in this case can mean *char* developent and overall widening of braiding and wandering rivers. Within the same cross-sectional area, widening means a proportionate decrease in mean cross-sectional depth. No information is available on the gradual decrease of mean channel depth. However, ISPAN (1993) observed widening in most of the rivers in the system. Also, there is the possibility that such sedimentation could have been counterbalanced by subsidence rates. But maximum subsidence rate of only 2 mm/yr has been reported by MPO (1987b).

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