The University of Nottingham

SEDIMENTATION, VEGETATION AND LAND USE DYNAMICS ON THE BRAHMAPUTRA-JAMUNA FLOODPLAIN, BANGLADESH

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ABSTRACT

This study investigated contemporary floodplain sedimentation, interactions between sediment, vegetation, and agricultural land use, and the potential utility for a Bayesian Network Decision Support System (BNDSS) to assist farmers in making better decisions concerning agricultural land use. The research was performed around *Bara Bania Mouza* (village) under *Daulatpur Uazila* in *Manikgong* district of the Brahmaputra-Jamuna floodplain in Bangladesh. This area was selected because it is representative of the young and active floodplain, where the land is flooded and receives overbank sediment deposition every year. The research employed exploratory data analysis and Bayesian approaches to identify and investigate causal relationships among the variables and so support probabilistic inferences. The study investigated two distinctly different types of monsoonal flood: a *bonna* (an abnormally large flood that occurred in 2007) and a *barsha* (a normal flood that occurred in 2008). Data on landforms, flood hydraulics, sediment dynamics (suspended sediment concentrations and sediment accumulation rates), and vegetation, rain-fed flooding, land use and farmers knowledge on soil suitability and cropping were collected through field surveys. The results establish how flow and sediment dynamics contrast as a function of landform and demonstrate that the thickness and calibre of deposited sediment strongly influence farmers' decisions on which and how many crops to cultivate on a given plot. Natural vegetation (e.g. sun grass) and certain agricultural crops were shown to have huge potential for use in slowing floodwater and trapping coarse grain sediment particles in buffer stripes. Marked contrasts were also observed between the characteristics of sediment deposited by rain-fed and river water flooding. Questionnaires and semi-structured interviews revealed that although farmers have profound knowledge on soil types and crop associations their methods are crude and little or no science is involved in the investigation of soil and sediment properties. Despite this, farmers' estimates of soil properties proved to be reasonably accurate with the estimate of particle size differing by only <15% from the results of laboratory particle size analysis. This suggests that the farmers' methods do give reliable indications of key soil attributes, but that they could be improved if scientific information was integrated with their local knowledge. A Bayesian approach provides a means of achieving this and the BNDSS developed in this study was found to produce good results when compared to field observations and backward propagation indicated that for better decision making it is crucial to consider both physical and socio-economic variables. The findings of the research reported in this thesis show that sedimentation has major impacts on agricultural land use dynamics in the Brahmaputra-Jamuna floodplain and that both natural vegetation and agricultural crops significantly influence sediment movement and the way that deposition is distributed over the floodplain. In a wider context, flood, sediment, vegetation and agricultural land use dynamics are controlled by complex set of both physical and human phenomena that are challenging to describe, integrate, analyse and interpret in a single study. In light of this, it is not surprising that the findings presented in this thesis highlight important gaps in knowledge that need to be addressed through further research.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PHOTOGRAPHS

ABBREVIATION AND ACRONYMS

AEZ	Agro Ecological Zone
ADCP	Acoustic Doppler Current Profiler
BM	Bench Mark
BMD	Bangladesh Meteorology Department
BN	Bayesian Network
BNDSS	Bayesian Network Decision Support System
BWDB	Bangladesh Water Development Board
CEGIS	Centre for Environmental Geographic Information Services
IRRI	International Rice Research Institute
ISPAN	Irrigation Support Project for Asia and the Near east
FAP	Flood Action Plan
GBM	Ganges Brahmaputra and Meghna
GoB	Government of Bangladesh
HYV	High yielding variety
ID	Influence Diagram
IRRI	International Rice Research Institute
MPO	Master Plan Organization
PWD	Public Works Department
SOB	Survey of Bangladesh
SRDI	Soil Resources Development Institute
TBM	Temporary Bench Mark
VK	Vernacular Knowledge
WARPO	Water Resources Planning Organization

LIST OF BENGALI TERMS

The following terms have been widely referred to in the research and need to be explained. The meaning of some local terms varies from region to region but the broad sense remains the same.

Aman	Group of rice varieties grown in the monsoon season and harvested after the monsoon season.
Aus	Group of rice varieties sown in the pre-monsoon season and harvested in the Monsoon season.
Barsha	A condition of floodwater that inundates agricultural field without any vulnerability and usually does not hampered on human daily life. It is known as normal flood.
Beel	A natural depression whose centre stays wet throughout the dry season. It is source of dry season irrigation and natural fish farming in the floodplain zone.
Bonna	A condition of floodwater that inundates agricultural fields, roads and settlements with high vulnerability. It is known as abnormal or damaging flood.
Boro	A group of rice varieties grown in the dry season.
Chala	The flood free high lands and highly suitable for agriculture.
Char	Ephemeral alluvial land on active floodplains within or adjoining the river.
Chwak	The lands usually used for agricultural farming and inundated with floodwater even with low flood.
Dhigha aman	Local variety rice grown in monsoon season can support floodwater depth less than 1meter.
Dainchya	One kind of shrub vegetation, which leaves used for green manure, seed for cattle food and straw for fuel wood. Scientific name is *Sesbania sesban* (L.) Merr. Family is Fabacea.
Haat	Periodic rural market.
Kanda	The land intermingled with river cut offs, scours, swales, long and narrow natural levees are known as *kanda*.
Kandi	Village situated on a *kanda*.
Khal	Small stream or drainage channel. Only navigable in monsoon season and rest of the period of the year used for cultivation, often man-made.
Kharif	Pre-monsoon and monsoon growing season (typically March to October) characterized by rain and high temperatures. Crops grown are paddy, jute, sugarcane etc.
Khas bhumi	The government own the land but it is distributed to the local people on a temporary basis.
Kodal	Hoe
Kosh	Extremely acid soil unsuitable for plant growth

Mauza	Land administration unit comprising one or more villages, which contain a jurisdiction list number and a defined area.
Nal	The lands very suitable for agriculture.
Rabi	Post-monsoon and dry (typically November to February) growing season with low or minimal rainfall, high evaporation rates, low temperatures, and clear skies with bright sunshine. Crops grown are *boro*, wheat, potato, pulses and oil seeds etc.
Thana	The lowest unit of Government administration; (literally, police station)
Union	A unit of local government administration below the *upazila*.
Upazila	The third administrative unit in Bangladesh below the district (*Zila*). A *upazila* consists of several unions.
Vasha aman	Local variety rice grown in monsoon season can supports up to 3meters water depth.

CHAPTER 1 INTRODUCTION

1.1 Introduction

The tributaries, mainstreams and distributaries of three great river systems; the Ganges-*Padma*, the Brahmaputra-*Jamuna* and the *Meghna (GBM),* interlace Bangladesh, together constituting one of the world's most dynamic fluvial systems and forming the world's largest contemporary deltaic plain, with an area of around 100,000 km^2 (Goodbred *et al.,* 2003). The total catchment area of the three-river systems is about 1.65 million km^2, of which only 7.5% lies within the borders of Bangladesh (Sarker *et al.,* 2003) (Figure 1.1). The Ganges-Brahmaputra and *Meghna* (GBM) basin generates 120 million ha-m runoff annually, only 10% of which is derived within Bangladesh from monsoon rainfall. It has been reported that the runoff from these river systems annually carries about 1.1 billion tonnes of sediment (EGIS, 2000 and Sarker *et al.,* 2003). The vast runoff of water and sediment from the GBM basin means that the Ganges-Brahmaputra and *Meghna* system ranks in the top three rivers worldwide in terms of both sediment transport and water discharge (Schumm and Winkley, 1994).

Within this system, the large average discharge (20,200 m^3/s) and heavy annual sediment load (590 million t/yr) of the Jamuna River results in highly variable and dynamic channel processes that changing the shape, size and position of the river continuously and thus impact on the adjacent floodplain areas (Coleman, 1969; Sarker *et al.,* 2003; and Islam, 2006;). The physical geography of Bangladesh, coupled with the annual hydrograph, which features snowmelt runoff from the Himalayas and tropical monsoon runoff each summer, is responsible for a high frequency of flooding in Bangladesh (Elahi, 1991b). In fact, the relatively low capacity of the primary channel to convey floodwaters (which results from its braided morphology and frequent siltation) means widespread flooding occurs in Bangladesh more or less every year, though with highly variable duration and extent.

Almost 20% of the country is regularly inundated by over bank river flow, which occurs during an average monsoon flood, while approximately 37% of the land area is inundated by floods with a return period of 10-years. However, the overwhelming floods of 1987, 1988, 1998, 2004 and 2007 inundated around 40-60% of the country. The main cause of these catastrophic floods is the synchronization of discharge peaks in the three major rivers: Ganges, Brahmaputra (*Jamuna*) and *Meghna* (BWDB, 2007). During floods, the concentration of suspended sediment is high and large volumes of sediment are carried through overspill channels and in overbank flow. A percentage of this sediment is deposited and so siltation takes place recurrently on the floodplain. This drives the development of characteristic types of landforms on the floodplains through lateral and vertical accretion. Typical landforms include natural levees, crevasse channels and splays, active and abandoned floodplain channels, alluvial ridges, flood basins, back swamps or marshes, ox-bow lakes (*beels*) and clay plugs. The floodplains are recognized as large sinks for deposits of fluvial sediments. They experience periodic inundation by lateral flow, and play a vital role in supporting wetland ecosystems (Junk *et al.*, 1989; Goodbred and Kuehl, 1998). These issues are of national importance as almost 80% of the total land area of Bangladesh is composed of floodplain. This vast area is dependent upon its rivers to support agriculture and aquaculture, as well as diverse flora and fauna (Paul, 1997). The productivity of diverse wildlife habitats, fisheries, fields and forests on the floodplain depend critically on the annual flood cycle, in terms of its extent, its duration and its association with sedimentation. Therefore, floodplain sedimentation is considered as the principal driver of change in the floodplain environment, which is responsible for the existence, productivity, and interaction of the major biota in river–floodplain systems (Junk *et al.*, 1989). It is due to sedimentation, that dynamic change appears in the terrain and morphology of the floodplains of Bangladesh, both spatially and temporally.

Millions of people in Bangladesh rely on the floodplain, and rural economies depend totally on regular monsoonal floods, which are regarded as 'normal' and which bring potential moisture and fresh sediments to the floodplain to make the land fertile and increase agricultural productivity (Elahi and Rogge, 1990 and Paul, 1997,). Moreover, wetlands in the floodplain, particularly back swamps *(beels,)* also provide important habitat with enriched biodiversity. Wetlands and swamps further provide a major protein source for the human population in the form of a wide variety of fish species. A large number of people are engaged in catching fish from the floodplain wetlands (*beels*) as their livelihood. From this point of view, floodplains play a crucial role as a resource preserver to meet basic demands

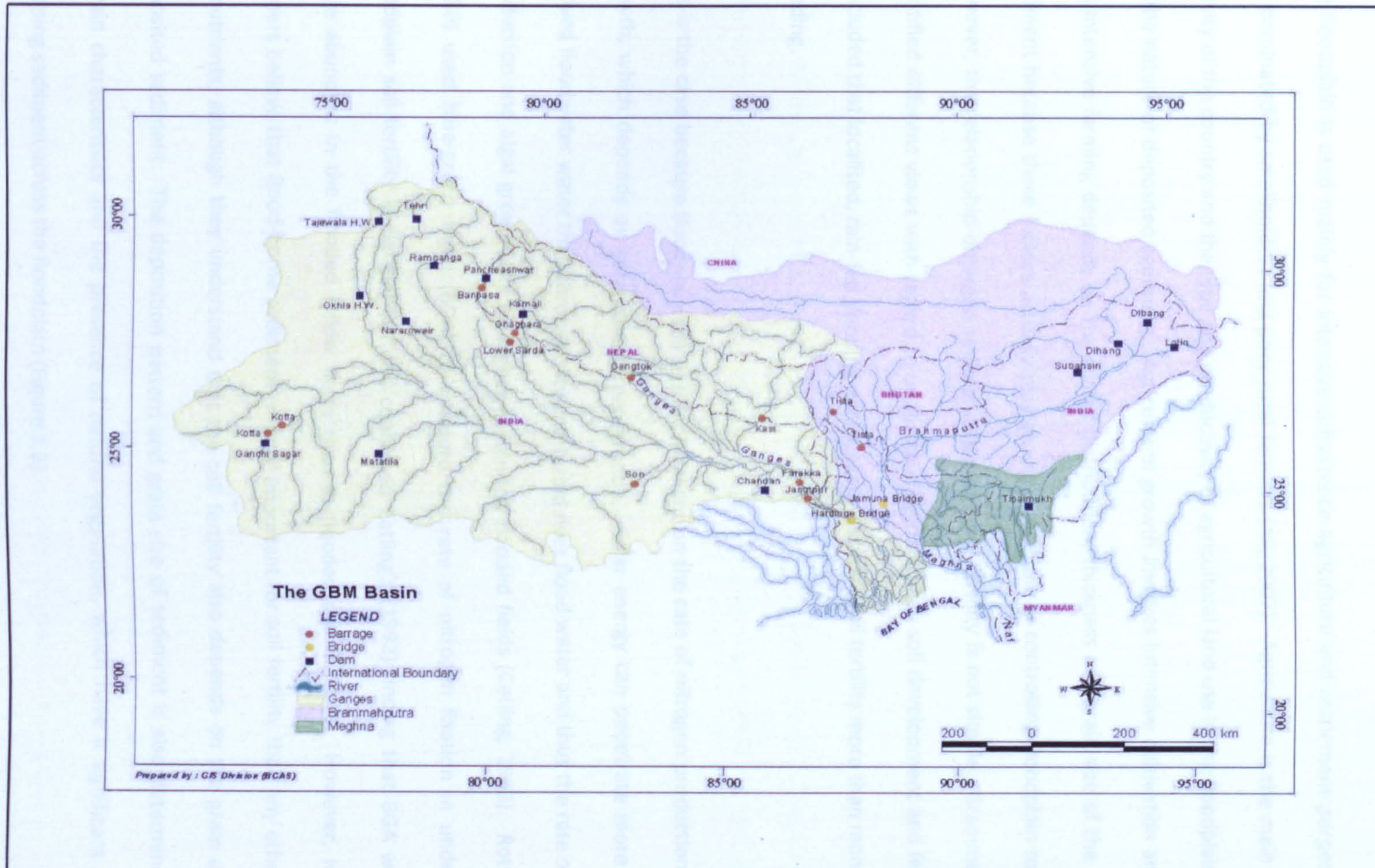


Figure 1.1 The Ganges Brahmaputra, and *Meghna* (GBM) Basin (Source: BCAS, 2008)

of the fast growing population (currently 147-milion with a growth rate 1.58 percent per annum) of Bangladesh (UNPRB, 2006).

The floodplain is used mainly for intensive subsistence agriculture and settlement purposes, which are dominated by smallholders and poor rural farmers (Ali, 2007). Agriculture is the main economic activity of the country and the type and productivity of agricultural land use in the floodplain depends on the nature of deposited sediment. Agricultural growth involves intensive cultivation and yield of this intensive farming depends on the spatial distribution, thickness and grain size of the deposited sediment because these factors actually play an important role in controlling floodplain soil fertility. However, the relationship between sedimentation and soil fertility is not simple. Brammer (1995b) identified different views with regard to understanding floodplain soil development and fertility and concluded that localised, rain-fed flooding may actually improve soil fertility more than monsoon river flooding.

This is the case because floodplain soil fertility is reliant on the rate of nitrogen production and algal growth, which depends on solar energy penetration. Solar energy can penetrate more with rain derived floodwater water than through silty and turbid river flood water and thus the rate of nitrogen production and algal growth will be higher in rain-fed flooded fields (Catling, 1992). Rother *et al.*, (1988) used blue-green algae (BGA) to measure the rate of nitrogen fixation in understanding floodplain soil fertility in Bangladesh and confirmed Catling's (1992) finding that BGA were much more abundant in the flooded fallow fields than in flooded paddy fields. However, indigenous farmers believe that flood-borne sediment is more important for soil fertility than any other sources of nutrients, although they understand that the soil fertility also depends on the grain size of the deposited sediment. The deposition pattern and grain size of sediment is also determined by the terrain characteristics and the presence of natural vegetation, which have a significant impact in trapping sediment across the floodplain (Figure 1.2).

As a result of contested views on the impacts of sedimentation during the past decade, increasing attention has been paid to the linkage between the river flooding, sedimentation and the floodplain environment. Scientists all over the world are now concerned about the dynamic nature of floodplain environments. Unsurprisingly, environmental scientists, particularly geomorphologists, have become increasingly interested in understanding the impact of sedimentation on vegetation and agricultural land use of the floodplain. In Bangladesh, there have been many studies associated with river dynamics but these have focussed mainly on the braid bar (*char*), attached bar (*char*) and deltaic areas of the great rivers. Following publication of Coleman's important paper of 1969, a great deal of research was undertaken on the Jamuna as part of the Flood Action Plan (FAP) for Bangladesh. Significant research projects relevant to the work reported in this thesis were performed by Thorne *et al.* (1993); Thorne and Thiagarajah (1994); Haggart *et al.* (1994); Thorne *et al.* (1995); FAP1 (1993), FAP4 (1993), FAP16/19 (1993), FAP19 (1995), and FAP24 (1996a-h); Paul (1997); Sarker, *et al.* (2003); Islam (2006); Sarker and Thorne (2006).

In addition, the Centre for Environmental and Geographic Information Services (CEGIS), Institute of Water Modelling (IWM)-formerly the Surface Water Modelling Centre (SWMC) and the Water Resources Planning Organization (WARPO) continue to carry out research in understanding the behaviour of the Brahmaputra-Jamuna River. Most of these studies have focussed on in-channel, morphodynamic changes, with particular emphasis on bar dynamics and bank line erosion.

The rivers of Bangladesh are highly dynamic and constantly changing their course, which ultimately affects all aspects of the adjacent floodplains. Despite being unable to fully understand or predict the morphological behaviour of braided rivers, researchers have explained some important characteristics of these fluvial systems and their dynamics, especially with respect to fluvial processes and sediment transport (Best *et al.*, 2007). Although, there is a great deal of existing published research on the rivers of Bangladesh, containing a considerable amount of information on channel morphology, bank erosion and delta formation (Bristow, 1993; Thorne *et al.*, 1993; Ashworth *et al.*, 2000), there is still a paucity of data concerning sedimentation driven by overbank deposition in Bangladesh.

During the early 1990s, an attempt was made by ISPAN (1995) to study floodplain sedimentation rates across the country, but this yielded little quantitative information due to the fact that major floods event occur only episodically. Recently, Goodbred and Kuehl (1998) used ^{137}Cs and ^{210}Pb radioisotope geochronology techniques to investigate accumulation rates of sediment in the Bengal Basin. However, although this is a powerful technique, it only provides information on accretion rates averaged over 50 year periods rather than revealing the amount of sediment deposited during single annual events.

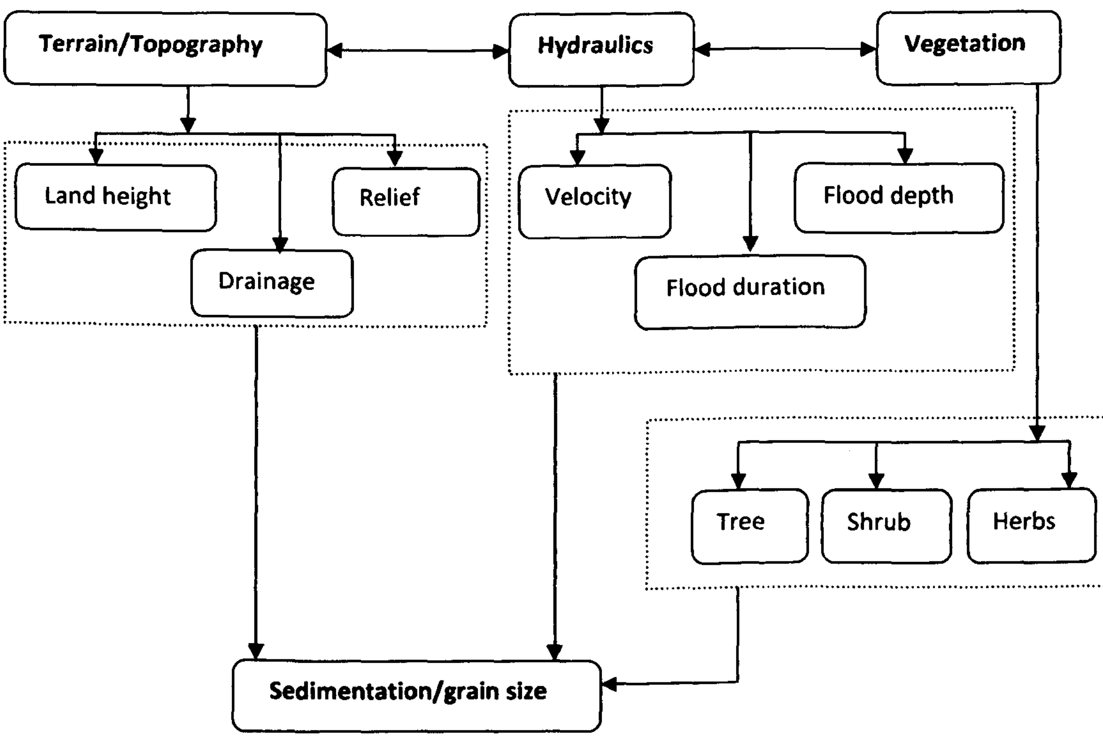


Figure 1.2 Flow chart show the linkage among the physical factors, Sedimentation and grain size on the floodplains of Bangladesh

In Bangladesh, subsistence and intensive farming rely on annual and inter-annual variation in sedimentation processes. Therefore, there has been a long debate on the role of deposited sediment in agriculture, and whether it is or is not good for agriculture. Currently, the demand for improved knowledge of floodplain sedimentation is greater than ever and growing fast due to its potential for informing human decision making concerning land use and other activities on the floodplain. This demand has not been sufficiently researched yet. Considering these factors, an investigation into the complex natural phenomenon of floodplain sedimentation and its interaction with human activities and land use in the floodplain sedimentation of the Jamuna River may shed light on the floodplain environment of Bangladesh and how its use may be improved, made more sustainable and even optimised.

As the floodplain is so important to people's livelihoods in Bangladesh, comprehensive research more specifically directed towards the floodplain must now be undertaken. This research needs to investigate the effects of floodplain sedimentation on agricultural land use, how vegetation traps sediment and how sedimentation impacts different types of vegetation. These issues must be understood in order to manage or mitigate the adverse impacts of sedimentation, enhance the benefits of sedimentation and improve the lives of people who live and work on the floodplains of Bangladesh. The research work reported in this thesis makes a modest attempt to address these gaps in knowledge and should assist policy makers to develop more efficient planning strategies for adaptive floodplain management that are sustainable in the context of the floodplains of Bangladesh.

1.2 Research Questions, Aims and Objectives

Bangladesh is a state that is dependent upon agriculture, where approximately two-thirds of the population work in the agricultural sector and mostly through growing crops on the floodplains. To meet the basic demands of the rapidly growing population, the floodplain has experienced agricultural intensification during the last 30 years (UNPRB, 2006; Ali, 2007) increasing the dependency of the nation on high yields from its floodplains. Agricultural production depends on the monsoonal flooding and the nature of the sediment deposited during the monsoon flood. Therefore, it is imperative to investigate floodplain sedimentation processes and how the sediment interacts with natural vegetation, standing crops and human land use more generally. In this context, the work undertaken in this doctoral research aimed to find answers to a number of specific research questions.

1.2.1 Research questions

This research aims to answer the following research questions:

1) How was sediment deposition distributed throughout the study area in 2007 and 2008 and what factors are responsible for this distribution (deposition thickness and particle size distribution)?
2) How does sedimentation interact with human land use and vegetation? This question has two components:
    a. What is the impact of sedimentation (sand, silt or clay) on agricultural land use and how does rainwater flooding, which is sediment-free, contrast with river flooding?
    b. How does vegetation (e.g. Sun grass - *Imperata cylindrica* (Linn.) (Rauschel, Graminea/Poaceae) act to trap sediment?

This second question is especially important for sedimentation control using buffering strips. Brammer's study (1995b) suggested radical new thinking in floodplain sedimentation and soil fertility. The common belief of Bangladeshi farmers is that the floodplain soil is more fertile due to regular inundation with sediment-laden river water. However, a survey conducted by FAO (1971) questioned this popular belief. A vast area of floodplain was found to be inundated by rainwater rather than river water. The soils of the rainwater flooding area were found to have well developed profiles with strongly acidic top soils, which showed no evidence that they receive regular addition of river sediments. Brammer (1995b) raised the question that *"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 or periodic increments of new alluvium?"* (ISPAN, 1995:1-10). The idea that flooding rather than sedimentation may be responsible for the fertility of floodplain soils is potentially seismic in importance but has never been independently corroborated or refuted. In addition, if coarse sedimentation is more of a threat to fertility than a benefit, there is huge potential for buffering strips to protect agricultural fields from sand deposition, but research is needed to establish the effectiveness of different types of vegetation and width of buffering strips.

3) How do farmers account for sedimentation when deciding what crop to grow on a plot of land? Could they make better decisions if they had better information on sedimentation?

4) How do farmers decide on land use more generally and would a Bayesian Network Decision Support System assist them? This would be entirely new to Bangladesh and would introduce a new and potentially valuable tool to assist with land use decision making.

1.2.2 Research Aims and Objectives

The Brahmaputra-Jamuna floodplain is typically dynamic and subject to marked change over short time periods due to the nature of the annual flood events which alter the river course very frequently through in-channel siltation and bank erosion. The floodplain also changes year-on-year due to overbank deposition and, in places, scour. These sedimentation processes are driven by the hydrodynamic characteristics of the flow and the supply of sediment from local and upstream sources. On the other hand, the land use pattern (agriculture, settlement, road, etc.) and natural vegetation also exert major influences on sedimentation processes. Consequently, sedimentation process vary between managed and unmanaged areas of the floodplain. The managed floodplain is the land that is under intensive farming and the unmanaged floodplain is land that is seldom used for agriculture. As agriculture is the main land use on the floodplain, it is also crucial to examine how farmers take the decision to plant crops on a particular piece of land, considering, amongst other things, the sediment characteristics of the floodplain. That is why floodplain sedimentation has been selected as a driver that influences human land use dynamics. Another important phenomenon that has been identified on the floodplain is that some particular types of vegetation (e.g. Sun grass - *Imperata cylindrica* (Linn.) Rauschel, Graminea/Poaceae) are especially effective in trapping sediment, and actually act to filter the amount and grain size of sediment in transport. This is obviously very important to agricultural crop production in areas downstream of a stand of Sun grass. Therefore, the present research aims to make a bridge between the natural process and the farmers' use of vernacular knowledge in decision making on land use, through which farmers might use information gained from actually detecting and analysing sediment deposition rates in recent years, in relation to the magnitude and duration of annual flood events.

Given this vision for the scope of the work, the broad aims of the research are as follows:

1) Monitor sedimentation processes and distributions in relation to land use, human activities and floodplain vegetation.

2) Investigate how sediment characteristics vary within managed and unmanaged floodplain environments.

3) Discern how natural sediment processes affect human decision-making on land use.

Based on these aims, the objectives of the research fall into two broad categories. Firstly, methodological, which can be used for this study and perhaps for the wider academic community. Secondly, developmental, through which a practical perspective for Bangladesh can be derived that may be used by the 'elected' and 'appointed' policy and decision makers in understanding sediment processes and land use dynamics and which might be used to train or assist farmers who are directly involved with agriculture.

Seven specific objectives are addressed in order to satisfy the research aims:

i) To investigate the characteristics of the floodplain study area; hydraulics (over bank flow velocity, flood depth and duration) and terrain characteristics;

Research Approach and Utility: Collect data from a field survey during the monsoon season (considering the nature of the flood events) and record the data on base maps prepared through scanning and digitizing cadastral maps and topographic sheets. Determine the terrain characteristics, using cross-sectional levelling data and analyse through GIS techniques. The hydraulic and terrain characteristics of the floodplain may later help policy makers in adaptive planning of floodplains in Bangladesh.

ii) To Examine space and time variations in sedimentation for two monsoon seasons (2007 and 2008);

Research Approach and Utility: Measure sediment deposition rates due to each flood event and compare them to the grain size distribution considering the nature of flood hydraulics. The outcome also may be used to establish spatio-temporal scenarios for floodplain sediment deposition that could be useful for floodplain management processes through adaptive land use policy.

iii) To assess spatial and temporal variation of agricultural land use patterns;

Research Approach and Utility: To develop a spatio-temporal agricultural land use index in understanding the impact of seasonal and annual variations, which might be useful as a guide for agricultural planners to use the land more optimally.

iv) To contrast the sedimentation characteristics associated with rainwater flooding and river flooding;

Research Approach and Utility: To examine the grain size of the sediments in areas affected by the two different types of flooding and how this is perceived by the farmers to affect agricultural crops. Agricultural specialists assisting farmers with sustainable agricultural development might then use these findings.

v) To document vegetation characteristics; identify how vegetation acts to trap sediment, how different grain sizes are affected by vegetated buffer strips.

Research Approach and Utility: To identify the interaction between vegetation (e.g. Sun grass-*Imperata cylindrica* (Linn.) Rauschel, Graminea/Poaceae) and sedimentation processes. This information could be useful when determining the significance of the vegetated buffer strips for sustainable floodplain sediment management.

vi) To document farmers' perceptions on sediment and agricultural land use;

Research Approach and Utility: To examine the farmers' vernacular knowledge in accounting for sediment in agricultural crop selection.

vii) To evaluate the effects of sedimentation on human decision-making concerning agricultural land use;

Research Approach and Utility: To contextualise the significance of sedimentation processes in affecting farmers' agricultural land use decisions and help explain land use dynamics at the plot scale (as illustrated on the *mauza* (village) maps). Land use decisions rely on both physical and human factors. As Bayesian networks provide a framework for predicting prior and conditional probabilities of the human and physical variables following Bayes's rule, it is worthwhile to integrate physical and human processes through a Bayesian Decision Support System(BNDSS) (chapter 7 section 7.2).

1.3 Rationale of the research

Bangladesh lies in an active tectonic zone, which comprises of hill (12%), terrace (8%) and floodplain (80%) terrains (Brammer, 2002:5). According to FAO (1988), the country is classified into 30 different agri-ecological regions, including five main kinds of floodplain. These are: active river floodplains meander floodplains, piedmont floodplains, estuarine floodplains and tidal floodplains. The main floodplains are ascribed to the major river systems, which are the Ganges, Brahmaputra-Jamuna and Meghna, but also include the smaller floodplains of literally hundreds of rivers and canals which criss-cross the 147,500 sq km land area of the country (Figure 1.3). The Brahmaputra-Jamuna is the main river flowing through the country from north to south and is responsible for the formation and development of both active and meander floodplains. These floodplains constitute ~60% of the total floodplain in Bangladesh and most of their area land is used for agriculture and/or human settlement. Sedimentation processes on the Brahmaputra-Jamuna floodplain are linked with the flooding regime of the Jamuna River and the long history of occupation of the floodplain means that indigenous people have a reasonable understanding of the relationship between flooding and sedimentation.

However, global warming and changes in catchment land-use are now causing the nature of flooding nature to change and this will ultimately affect floodplain sedimentation processes (Mirza, 2002, 2003a, 2003b; CCC, 2006). The floodplains of Bangladesh are subject to intensive use by millions of people who grow agricultural crops and live on them. They also have nested within them major wetland ecosystems, which have immense social, economical and biodiversity values. The fact is that all the attributes, uses and values of the floodplains depend on flooding, sedimentation and human land use. The majority of the people living in the floodplains are poor. They are mostly involved in intensive subsistence farming systems (Ali, 2007). Thus, the floodplains play a vital role in supporting peoples' livelihoods. However, it is known that rapid and largely unplanned development in the floodplain is producing widespread degradation of floodplain environments (IUCN, 2005a). In view of the precarious existence of the hundreds of thousands of floodplain dwellers and farmers, there is genuine and urgent need for undertaking efficient and sustainable management of floodplain environments. It is in this context that this doctoral research at the School of Geography, University of Nottingham, is considering one of the main drivers of floodplain dynamics: sedimentation processes and their interaction with natural vegetation and agricultural land use dynamics of the active floodplains of Bangladesh.

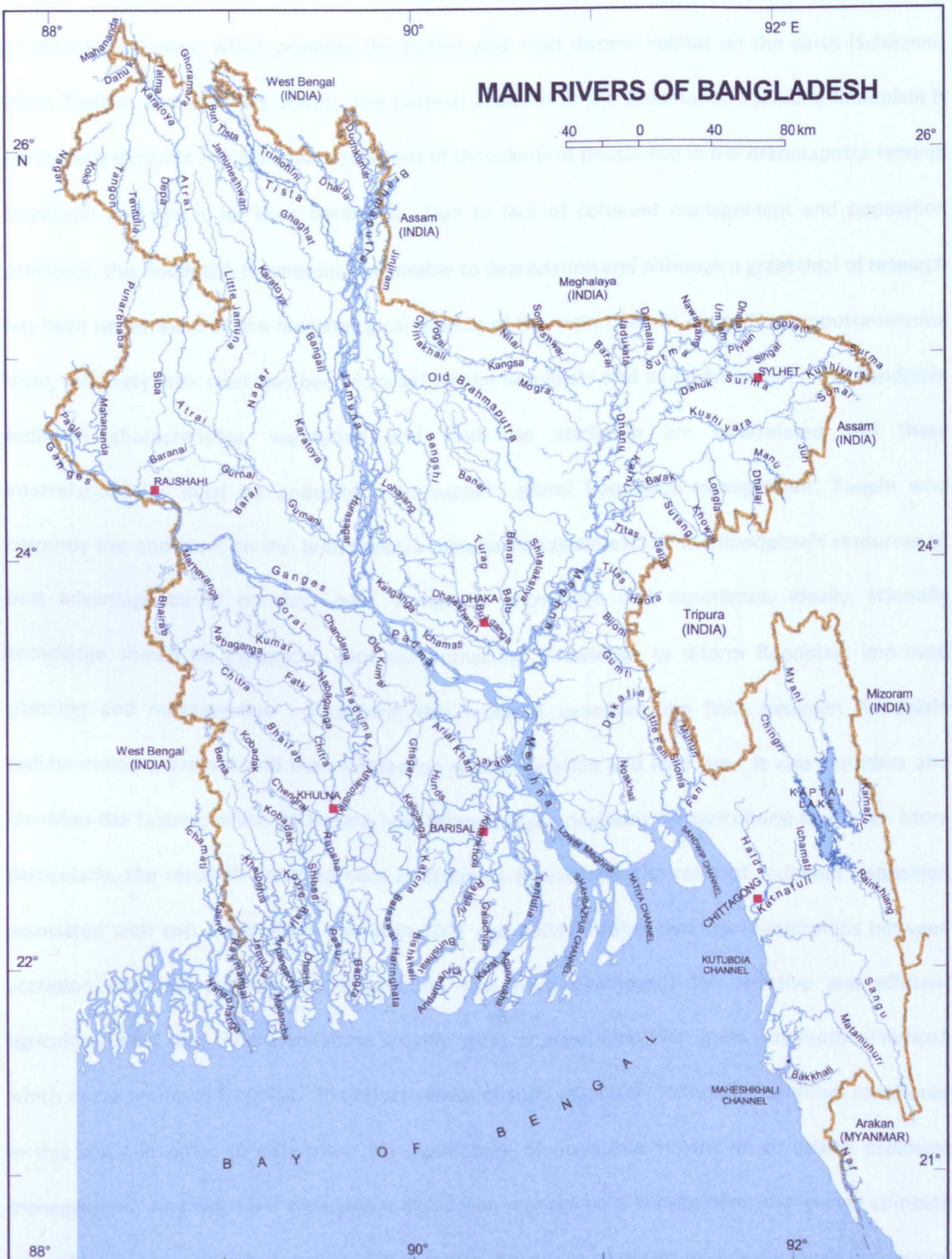


Figure 1.3 Main Rivers of Bangladesh (Source: BCAS, 2007)

1.4 Scope of the research

Most of the river courses in Bangladesh are alluvial, with shifting, meandering or braided plan forms that cause massive erosion and deposition and exhibit changes of course continuously. This affects the adjacent active floodplains. Thus, active floodplains are characterised by the changing hydrology of the adjacent river, which provides the richest and most diverse habitat on the earth (Schiemer, 2000; Tockner and Stanford, 2002). The channel adjacent to the Brahmaputra-Jamuna floodplain is particularly dynamic and complex. Hundreds of thousands of people live in the Brahmaputra-Jamuna floodplain and rely it for their livelihood. Due to lack of coherent management and population pressures, this floodplain is especially vulnerable to degradation and although a great deal of research has been undertaken on the morphological aspects of the main channel of the Brahmaputra-Jamuna River, relatively little work has been focused on the floodplain and its environment. The floodplain sediment characteristics, vegetation and land use attributes are interrelated and these interrelationships must be understood to support sound floodplain management. People who currently live and work on the Brahmaputra-Jamuna floodplain exploit the floodplain's resources to best advantage based on their own, vernacular knowledge and experience. Ideally, scientific knowledge should be integrated with the vernacular knowledge to inform floodplain improved planning and management. Therefore, this research examines the links between floodplain sedimentation processes and their interaction with vegetation and land use. It also considers and identifies the factors, which determine how farmers make decisions on agricultural land use. More particularly, the research reported here in attempts to establish the rates of sediment deposition associated with two major flood events in 2007 and 2008. It also explores relationships between accretion rate and particle size distribution that have significance for effective and efficient agricultural land use. There are some specific types of vegetation (Sun grass -*Imperata cilindrica),* which cause sediment trapping. The effectiveness of such vegetation in trapping sand has monitored in this study in order to determine the significance of floodplain vegetation to coarse sediment management. An integrated approach to floodplain management is suggested, that would combine scientific and vernacular knowledge of the natural processes to better inform decisions concerning land use through use of a Bayesian Network Decision Support System.

1.5 Thesis structure

The thesis is split into four parts:

1. Chapters 1, 2 and 3

Chapter 1 focuses on the primary issues of the study including background, the research questions, aims and objectives, rationale and scope of the research. A review of literature pertaining to floodplain processes and its uses is presented in the first half of Chapter 2. In the second half, and in light of this review, an attempt is made to identify research gaps concerning floodplain environments in Bangladesh. Chapter 3 presents the research design; study methods and data sets, including the field study and environmental setting of the study site. The information presented covers the physical and human attributes and rationale for study site selection. Methodologies and analytical techniques are further discussed in more detail in the subsequent chapters.

2. Chapter 4

Chapter 4 describes floodplain sedimentation characteristics and reports on the particle size distributions of the deposited sediment with reference to the flood hydrology and terrain characteristics of the study site. This part of the thesis addresses research question 1.

3. Chapter 5

Chapter 5 addresses research question 2, focussing on the interaction between sediment, vegetation and land use. A range of statistical techniques is applied to establish the form and significance of interrelationships among the variables. This part closes with discussion about the development of decision support systems.

4. Chapters 6 and 7

Chapter 6 addresses research questions 3 and 4. It examines the utility and application of the Bayesian Network developed to support improved land-use decision-making by exploiting both scientific and vernacular knowledge bases and experience. Research outcomes and possible uses for the most important and interesting findings are covered in this chapter, which considers the wider implications of the results. Finally, Chapter 7 briefly summarises the overall outcomes of the thesis together with recommendations for further research.

CHAPTER 2 CONCEPTUAL UNDERSTANDING ABOUT FLOODPLAIN ENVIRONMENT

2.1 Introduction

This chapter synthesises a conceptual understanding of floodplain environments developed through a review of the relevant literature. The first, second and third sections of the chapter comprises of a review of floodplain delineation, forms and processes, based on the published literature and with the aim of describing contemporary floodplain sedimentation in the context of the nation of Bangladesh. The fourth and fifth sections of the chapter address floodplain vegetation and land use related to sedimentation, focusing particularly on key and recent advances. Management issues and literature related to decision making are dealt with in the sixth and seventh sections, to provide an overview of importance of research needed for people living and working in the floodplain seek to alter its forms and functions to their benefit while sustaining floodplain resources.

One over-arching and significant outcome of the review reported here is that, while a great deal has been published nationally and internationally concerning fluvial sedimentation processes in Bangladesh, most studies have concentrated on bar *(char)* and in-channel deposition (e.g. Coleman, 1969; Williams and Rust, 1969, Rust, 1972; Smith, 1974; Ashmore, 1982, 1991; Ferguson and Werritty, 1983; Goswami, 1985; Davoren and Mosely, 1986; Bristow, 1987; Dawson, 1988, Thorne *et al.,* 1993, Islam, 2006) rather than sediment dynamics in the floodplain proper. The fact is that, notwithstanding the large number of sediment-related studies (Ashworth *et al,* 1994; Mosselman *et al.,* 1995; ; Sarker *et al.,* 2003; Sarker, 2004; Sarker and Thorne, 2006) relatively few articles focus solely on floodplain sediment processes, although some highlight the influence of sediment on flood vulnerability and damage suffered by people and properties in the floodplain. This is surprising given that, in Bangladesh, the floodplain is the most important component of the alluvial river landform system because it is where the majority of natural resources are found and where most human activities take place. Both the types of human occupation and land use, and sustainability of floodplain ecosystems depend to a great degree on rates and patterns of overbank sedimentation. Consequently, the lack of an extensive knowledge base means that it is crucial to perform and publish the further research necessary to detail and address the unresolved issues related to floodplain sedimentation, land use and vegetation. It is within this context that this chapter assesses the current state of knowledge on floodplain environments and provides the basis from which to identify key elements of floodplain research necessary to identify and investigate some of the more important unresolved problems facing the people who rely on the floodplain environment for their homes and livelihoods.

2.2 Floodplain Delineation and processes

A floodplain is defined as the strip of land relatively low and level, formed by sediment deposition along the course of a river and subject to frequent inundation by periodic floods (Bridge, 2003). Hydrologists and engineers define the floodplain as the surface next to the channel that is inundated once during a given return period regardless of whether this surface is alluvial or not (Hydraulic Engineering Centre, 1976; Ward, 1978). But this is termed the hydraulic floodplain and it is pointed out by Graf (1988) that geomorphic history does not play a role in its definition. Some geomorphologists go a little further than this, adding that, "the floodplain is a largely horizontally bedded alluvial landform adjacent to a river that is separated from the channel by natural levees, and built of sediment transported by the present flow-regime" (Nanson and Croke, 1992:460). This definition is known as the genetic floodplain, which describes the landform as contemporaneous with present hydroclimatic conditions. Thus, the floodplain is defined as relatively low and level land, adjacent to river, and usually formed by river borne sediment with diverse flooding characteristics. Floodplains work as a central point to sediment storage and exchange processes in the zones of transfer and accumulation (Schumm, 1977), are built through vertical accretion of flood-borne sediment, coupled with lateral deposition and re-working driven by channel migration (Leopold *et al.*, 1964 and Pickup, 1991) and are regulated naturally by the fluvial system.

Schumm (1977) divided the fluvial system from the headwaters to river mouth into zones of sediment production, transfer and deposition (Figure 2.1). In this schematized representation, the upper reach is predominantly a sediment supply zone, which provides sediment that is transported through the middle reaches (zone of transfer) before being deposited in the downstream reaches (zone of deposition). The landforms that characterize the river landscape vary between these zones, reflecting differences in drainage network form, fluvial processes, and channel patterns responsible for forming the predominant features of the floodplain. In the upper course, valleys are usually narrow, limiting floodplain width. In the middle and lower courses, there is a general notion that braided channels are associated with shifting of the course of the river that is continuous and extensive, so that the floodplains are frequently reworked and their environments are not well developed (Nanson, 1986). Conversely, the floodplains of rivers with sinuous or meandering channels have more mature environments as the channel migrates slowly and within a more stable meander belt, that allows floodplain landforms to be more developed than in the braided environment (Nanson and Croke, 1992). Indeed, the reason for a lack of knowledge of floodplain sedimentation processes is partly due to the fact that most studies have been based on quasi-stable meandering channels. Whatever channel pattern exists, floodplain development is independent of channel pattern, noting that large, alluvial rivers such as the Mississippi, Amazon and Brahmaputra display similar floodplain forms and features despite having contrasting plan form patterns (Bridge, 2003).

Although Bridge's argument contradicts the conventional views of floodplain formation, it explains in terms of discharge, sediment volume and overbank deposition characteristics and the formation of different types of alluvial depositional features, which exist in similar patterns along all large rivers around the world.

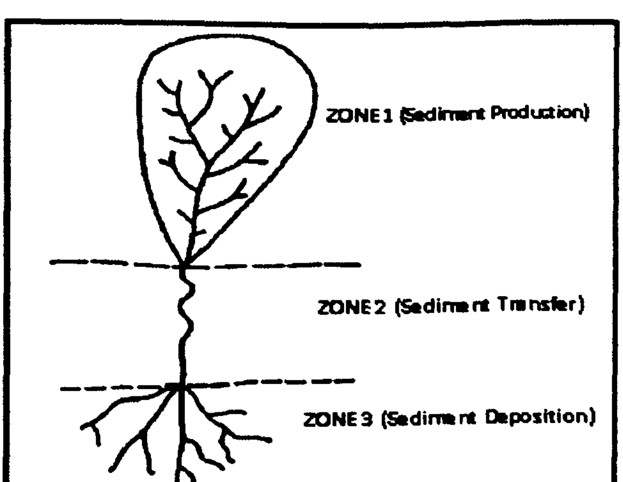


Figure 2.1 The Fluvial System (after Schumm, 1977)

Bridge (2003) classified the floodplain into two broad categories; flood basins and alluvial ridges in terms of floodplain geometry (Figure 2.2). This type of specification usually best appears in the meandering channel plan form environment, where floodplain form and development are comparatively stable, but it poses a limitation for a large, anabranching, braided river like the Brahmaputra–Jamuna in Bangladesh, where alluvial ridges alter regularly due to the recurrent, large flood floods. Thus, it is relatively difficult to define the floodplain geometry for large rivers. The distribution of the alluvial features, within the flood basin includes back swamps, marshes, lakes, and floodplain drainage channels formed in weak or unconsolidated sediments. The alluvial ridges comprise of natural levees and crevasse splays formed in relatively coarse, more consolidated sediments associated with active and abandoned channels. These features are common to most large river's floodplains, including those of the Brahmaputra-Jamuna River. However, while the features typical of floodplain topography are almost universal, their characteristic dimensions may vary from a few metres to tens of kilometres depending on the scale of the river that produces them and the nature of its flooding regime (Bridge, 2003).

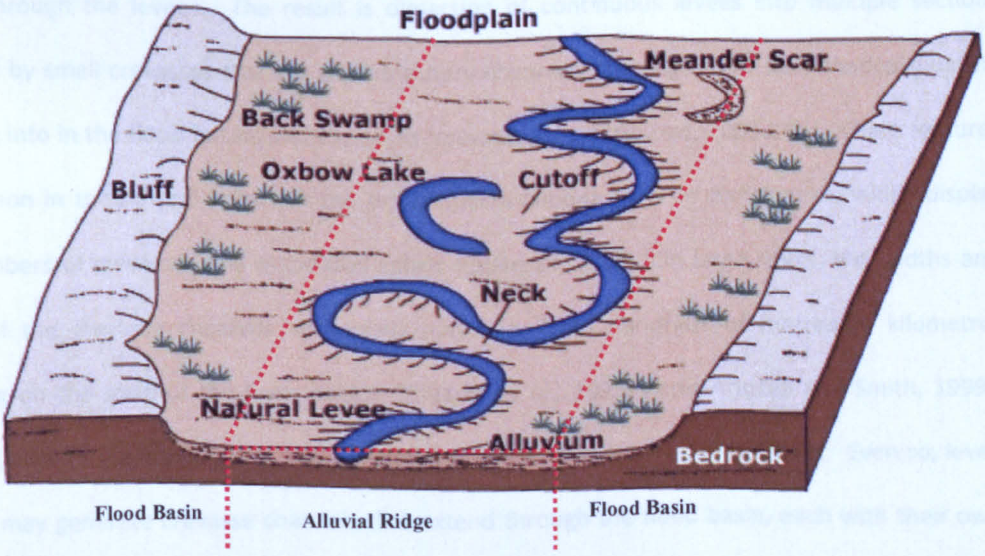


Figure 2.2 Floodplain consists of flood basins and alluvial ridges (Bridge, 2003)

Among all geometric features, the natural levee is one of the most important floodplain landforms. Because it is the closest floodplain landform to the channel, in terms of sedimentology, it is a zone of intermediary deposits that are generally finer grained than those of the channel bed load but coarser grained than those in the flood basins (Miall, 1985 and Collinson, 1996). Due to fining of the characteristic grain size of depositional sediment with elevation and distance from the channel, the cross-profiles of newly formed levees are generally narrower and steeper than those of older ones. As the grain size of deposited material decreases with distance from the channel, levee slopes are gradually reduced with distance from the channel towards the flood basin (Cazanacli & Smith, 1998). The channel plan form influences deposition patterns in ways that may change the dimensions and geometry of levees. For example, along the meandering course of the Lower Mississippi River, the relatively slow rate of meander shifting allows levees to grow to elevations as much as 6 m above the flood basins (Bridge, 2003 and Kolb, 2006). However, along the braided course of the Brahmaputra-Jamuna River, which is characterized by rapid shifting of the bank lines, levees rise only 2-3 m despite the fact that discharge of the river and its sediment load both exceed those of the Lower Mississippi (Coleman, 1969).

During large floods, flow breaches or spills over the levees to generate crevasses that develop by erosion through the levees. The result is dissection of continuous levees into multiple sections separated by small crevasses that act as distributary channels, forming fan or lobe-shaped deposits extending into in the flood basins and known as 'crevasse splays' (Bridge, 2003:261). These features are common in the natural levees of the Brahmaputra-Jamuna River in Bangladesh, which display large numbers of crevasses and associated splays (Coleman, 1969). On large rivers, the widths and lengths of the crevasse channels and splays may vary from hundreds of metres to kilometres depending on the scale of the levee breach (Bristow *et al.,* 1999; Perez-Arlucea and Smith, 1999). Generally, flow through a crevasse is ephemeral because it only occurs during floods. Even so, levee breaches may generate crevasse channels that extend through the flood basin, each with their own levees and terminal mouth bar forming a delta or fan that may be remote from the main river (Coleman, 1969; O'Brien and Wells, 1986; Bristow *et al.,* 1999). Although substantial research has been performed to identify the crevasse channels and splays of the larger river, the detailed studies necessary to describe the geometries and sediment characteristics of these common and extensive features have yet to be performed. During large and, particularly, long duration floods, large quantities of flow and suspended sediment leave the channel to enter the floodplains via crevasse channels. Consequently, these channels build the characteristic ridge-landforms that divide the floodplain into flood basins (Bridge, 2003).

Within Bangladesh, the floodplains of the Brahmaputra-Jamuna River feature all of these alluvial features, on a large scale as the floodplain width varies from 10 to 100 kilometres and extends along both banks for the entire 220-kilometre length of the river (Best *et al.*, 2007). However, floodplain delineation for large rivers is very complex. In particular, large river floodplains like Mississippi and Brahmaputra-Jamuna floodplains are more complex due to high flood variability. Apart from the crevasse splay, avulsion channels play an important role in depositing sediments on large river floodplains; including the floodplain of the Brahmaputra-Jamuna River in Bangladesh. The Brahmaputra-Jamuna floodplain is formed by partial avulsion, which results in anastomosing channels and distributary channels (Coleman, 1969; Slingerland and Smith, 2004) (Figure 2.3).

The floodwater of the main channel of Brahmaputra-Jamuna flows through hundreds of distributaries and sediment is distributed far away from the principal channel. As a result, different types of erosion and depositional features form on the floodplain as a function of the distance from the rivers. Thus, the floodplain comprises of a variety of geomorphic features, with different spatial scales, some active and others relict. In addition, due to seasonal and event-related flow variability the channels crossing the floodplain and dividing it into flood basins include both ephemeral and permanent watercourses, seasonal and perennial lakes and wetland marshes (*beels*) (Figure 2.4).

Until 1970s, the literature on floodplains was dominated by few case studies of very specific types, for example, the floodplains of the Mississippi (Fisk, 1944 and 1947), Watts Branch (Wolman and Leopold, 1957), the Klaralven (Sundborg, 1956) and the Brahmaputra (Coleman, 1969). Anderson *et al.* (1996) edited an important monograph on floodplain processes that deals with contemporary research, raises questions for discussion and outlines potential research needs. Problems with data capture and theoretical issues are presented in the context of understanding of the fluvial environment and, more particularly, floodplain form and development.

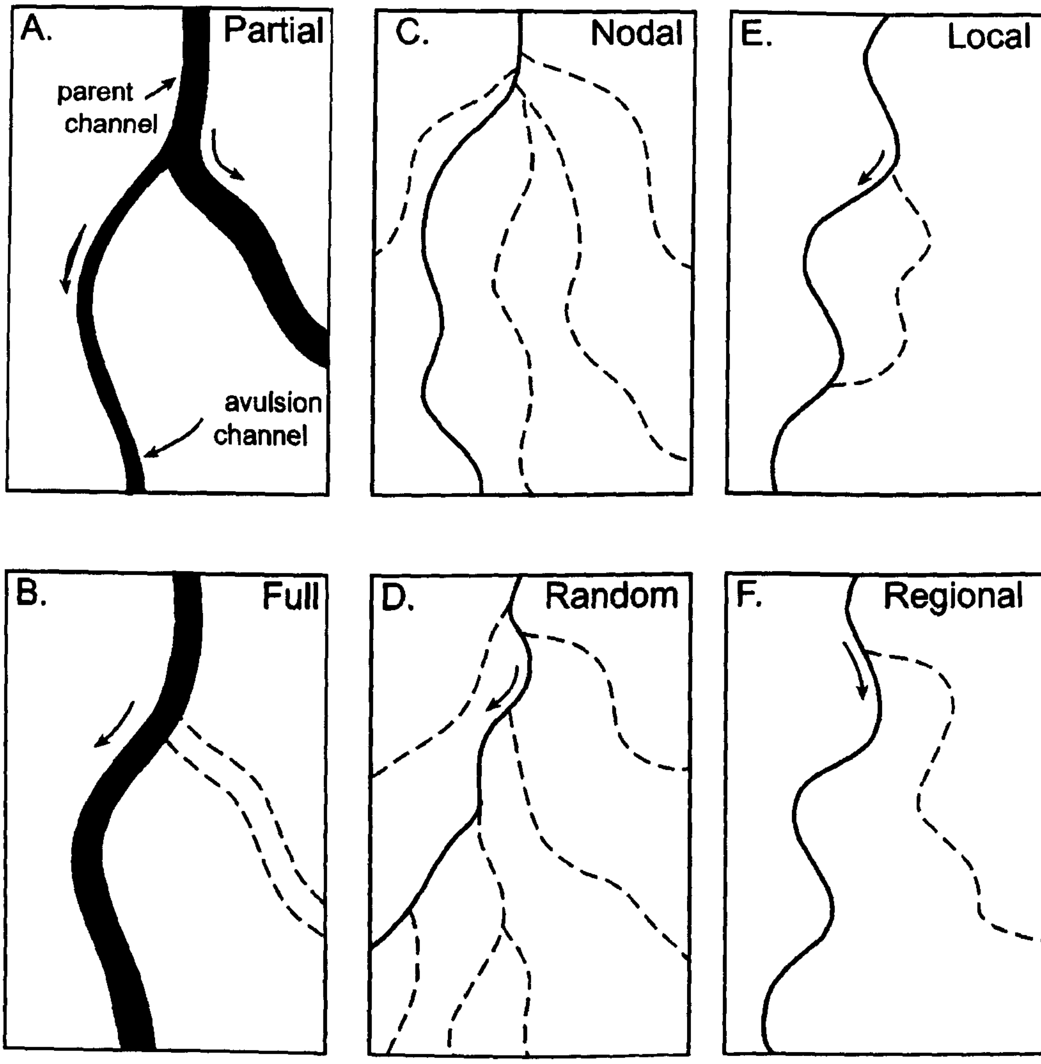


Figure 2.3 Sketches illustrating the Avulsion channels.
[Note: Solid lines active channels; dashed lines abandoned channels. Pairs A-B, C-D, E-F, refer, respectively, to proportion of diverted discharge, location of avulsion sites, and areal scale of avulsion.
(Source: Slingerland and Smith, 2004: 260)

In general, there are two categories of depositional processes: lateral and vertical, which form floodplains. Lateral deposits are formed by channel migration (Figure 2.5), while vertical accretion occurs through over-bank deposition during floods (Figure 2.6). In an early hallmark study on the floodplain formation, Leopold and Wolman (1957) concluded that lateral processes driven by point-bar accretion and braid-channel evolution were primarily responsible for building the floodplain, with vertical accretion adding a layer of finer material carpeting the main sediment body.

Figure 2.4 Anastomosing channels and different plan form featuresf the Brahmaputra-Jamuna River in Bangladesh (Source: EGIS, 2000)

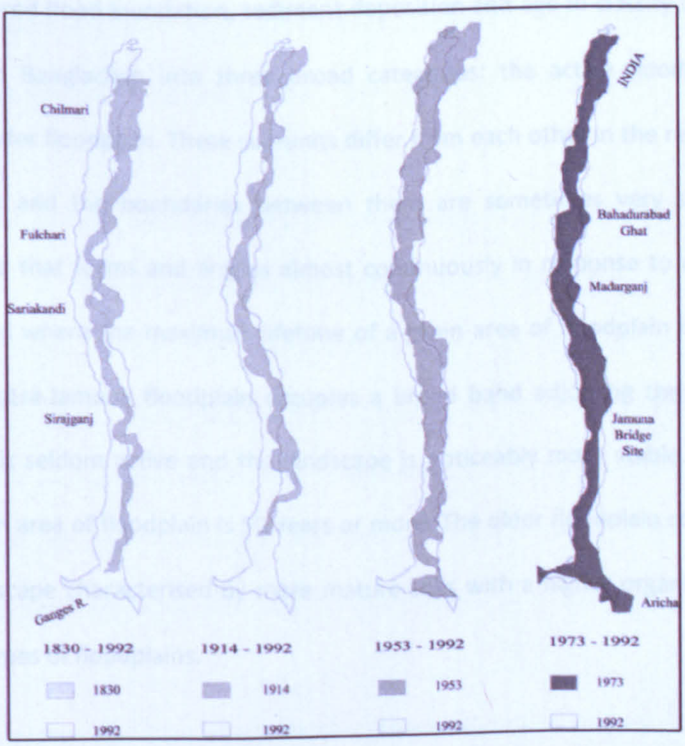


Figure 2.5 Later channel migration shows the historical floodplain development of the Brahmaputra-Jamuna river (Khan and Islam, 2003:962)

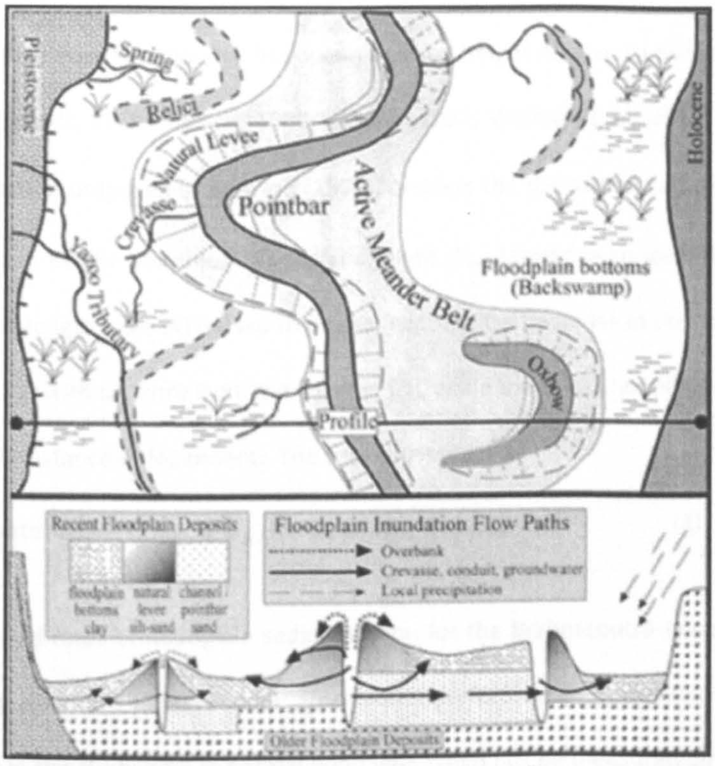


Figure 2.6 Overbank floodplain deposition and flows paths
(Source: Hudson, 2008:764)

FAP19 (1995) considered flood inundation, sediment deposition and age to classify the Brahmaputra-Jamuna floodplain in Bangladesh into three broad categories: the active floodplain, the young floodplain, and the older floodplain. These sub-units differ from each other in the relative maturity of their relief and soils and the boundaries between them are sometimes very sharp. The active floodplain is the zone that forms and erodes almost continuously in response to dynamic channel-shifting processes and where the maximum lifetime of a given area of floodplain is about 30 years. The young Brahmaputra-Jamuna floodplain occupies a broad band adjoining the active floodplain where bank erosion is seldom active and the landscape is noticeably more stable. As a result, the average lifespan of an area of floodplain is 50 years or more. The older floodplain comprise a smooth ridge and basin landscape characterised by more mature soils with a higher organic matter content than the other two types of floodplains.

Thus, floodplain deposition sequences provide a better understanding of floodplain processes and classification because the deposition sequences depend on the distance from the channel and its height relative to the channel. In fact, a great range of models predicts the overbank deposition rate as a function of distance from the channel, floodplain age and height relative to the channel (Wolman and Leopold, 1957; Everitt, 1968; Nanson, 1980; Pizzuto, 1987; Walling *et al.*, 1992; Howard, 1992). For example, an equation proposed by Howard (1992), predicts the deposition rate (ϕ) as a function of maximum floodplain height (maximum floodplain height [E_{max}], relative to local floodplain height [E_{act}]). Here, diffusion length scale (λ) is used to predict exponential decrease in the coarse suspended load deposition rate (μ) with distance from the channel (D), while the fine- grained fraction deposition rate (v) is modeled as distance-independent. The resulting model is:

$$\text{Deposition rate } (\phi) = (E_{\max} - E_{act})[\nu + \mu \exp(-D/\lambda)] \qquad (1)$$

ISPAN (1995) measured rates of floodplain sedimentation for the Brahmaputra-Jamuna floodplain in Bangladesh by using Howard's (1992) model. The model performed badly because the quantity of sediment deposited in the study area in normal flood year could not be measured directly because of the low flood level in 1994. Only a few areas along the rivers and nearby low-lying land were inundated by river water and received sediment deposits and there, the model performed well. It may be concluded from that specific study that Howard's model might well have performed better in a high flood level area, such as the events of 1988, 1998, and 2007 in Bangladesh.

Although a consensus has emerged regarding the importance of overbank deposition and vertical accretion in creating floodplain architecture, no comprehensive, quantitative model of overbank deposition is yet available. ISPAN (1993) identified two main reasons for the paucity of floodplain sedimentation models. Firstly, a limited number of 'ground-truthing' studies have been undertaken, which means that the direct measurements of sedimentation rates in floodplains needed to check and calibrate models are rare. Secondly, the complexity of overbank sediment transport and deposition processes has so far prevented their representation in a comprehensive model.

In theory, deposition rates might be predicted from floodplain sedimentology and stratigraphy, but this is difficult in practise. This is the case first because of the limited accuracy of the techniques involved in stratigraphic data collection and second because the coring and trenching required to access buried sediments are resource-intensive. Thirdly, the archaeological and age-dating techniques necessary to establish the sediment deposition rate are difficult and expensive to apply, especially outside developed countries (Brakenridge, 1984, 1985; Brown 1987, 1990; and Walling & Bradley, 1989).

Another approach to estimating sedimentation rate is based on constructing a sediment budget for the floodplain. In this approach, the rate of deposition is calculated based on the difference between sediment delivery to and removal from the floodplain. Hence, the concentration of suspended sediment in over-bank flow is the most important parameter in the floodplain sedimentation budget and investigators have used various techniques and instruments to measure suspended. Wren *et al.* (2000) used automatic water samplers and USGS DH-48 depth-integrated samplers to obtain unbiased point estimates of suspended sediment concentration. However, this technique poses considerable problems for long-term monitoring, particularly if the study site is located in a remote area and/or flood events occur irregularly. This is the case because auto samplers require regular field visits by an operator and it is essential to compensate for their temporally discrete nature by establishing suspended sediment concentration and discharge curves. The use of turbidity sensors for estimating suspended sediment concentration can overcomes the limitations of temporally discrete sampling methods and has long been advocated (Gippel 1989, 1995). However, suspended sediments contain a range of particle sizes, which can affect the response of sensors to turbidity, and so physical sampling is still required to establish a suitable calibration curve (Foster *et al.*, 1992; Gippel, 1995; Clifford *et al.*, 1995). Calibration problems can be overcome by collecting suspended sediment samples in bottles submerged in the water column at turbidity instrumentation sites over the course of the monitoring period and using these to calibrate and validate the concentrations estimated from turbidity (Brasington and Richards, 2000). Thonon *et al.* (2005) studied contemporary sediment settling characteristics in floodplains of the Rhine River using LISST-ST in situ measurement techniques. The LISST-ST is a suspended sediment trap that monitors the settling of the enclosed suspended sediment by laser diffraction in a cylindrical settling tube of 50mm diameter and approximately 33cm in height. Compared to other sensor and manual techniques, the LISST_ST provides more accurate sediment concentration rate, which is significant in establish a relationship between overbank settling velocities and grain size distribution in floodplain environments. Thus, this approach could be used to calibrate floodplain sediment budgets.

It is clear that, since the seminal research work by Leopold and Wolman (1957), a great deal of research has been undertaken on floodplain formation and development at a variety of scales. These studies have established that under different conditions floodplain form and historical development may be dominated by channel migration, vertical accretion or the dynamics of overspill channels flowing between flood basins. Despite the progress made in understanding floodplain-forming processes, no generally applicable, quantitative model of floodplain sedimentation has emerged.

From the above discussion, it may be concluded that the natural geometry of floodplains results in various forms, which are frequently adjusted by processes associated with lateral channel migration, large-scale avulsions, crevasse channels and splays, and overbank scour/deposition of sediment by the main river. In a hydrological and geomorphological context, floodplain geometry and its adjustment depend on the frequency and magnitude of floodwater flows and associated sediment transport, as they interact with floodplain terrain and vegetation.

This review of the literature on fluvial processes and floodplain formation has revealed that most research has been performed on relatively small, meandering and gravel-bedded rivers, with the majority of studies focusing on channel processes and dynamics together with relatively simple approaches to classifying floodplain processes based on factors such as floodplain age, elevation and distance from the channel. As the Brahmaputra-Jamuna is highly variable in terms of discharge and sediment load and the floodplain is mainly governed by the rivers' hydrological characteristics, it is difficult to delineate the floodplain types using a single classification.

2.3 Floodplain sedimentation: Measuring Techniques

A wide range of techniques and instruments have been used to measure sedimentation rates around the world. Methods used for the reconstruction of past floodplain sedimentation rates include analyses of sedimentary structure (Kilmek, 1974; Brown, 1983), radio carbon dating (Alexander and

Prior, 1971), fallout radionuclides such as Cs-137 and Pb-210 (Ritchie *et al.*, 1975; Walling *et al.*, 1986, 1992; Walling and Bradley, 1989, Walling and He, 1997; Allison *et al.*, 1998; Goodbred and kuehl, 1998; Aalto *et al.*, 2003), trace metal concentrations (Leenaers, 1989; Knox, 1989, 2006) and use of other horizons of known age (Costa, 1975 and Trimble, 1983). Contemporary rates of sedimentation can be estimated from an analysis of conveyance loses (Walling *et al.*, 1986; Walling and Bradley, 1989) where sedimentation rates are sufficiently large. For short- term sediment accumulation, after a single flood year, deposition can be measured using artificial marker beds and sediment traps that capture sediment even with very low rates of deposition and by repetitive topographical surveys (Mansikkaniemi, 1985; Walling *et al.*, 1986; Gretener and Strömquist, 1987; Walling and Bradley, 1989; Hooke, 1995; Asselman and Middelkoop, 1995).

Most available research study reports rates of the medium and long-term sediment accumulation based on environmental radionuclide techniques. For example, Aalto *et al.* (2008) investigated the processes of sediment exchange between the Strickland River in Papua New Guinea and its lowland floodplain by using ^{210}Pb Geochronology of floodplain cores to measure deposition rates over the past 65 years. This research also supports measurement of the reworking of material in the floodplain due to channel migration, which could balance the overbank deposition. The same type of study was conducted by Piegay *et al.* (2008) to document sedimentation rates on the floodplain of the Ain River, France at the decadal spatial-temporal scale by using dendrogeomorphic analysis, and the fallout radionuclides ^{137}Cs and unsupported ^{210}Pb. Measured sedimentation rates ranged between 6.5 and 24 mm per year on floodplain surface and channel infill sites, respectively. The research also established that channel degradation, aggradations, and bank erosion all act to reduce or increase the sedimentation rate. The results show that the outcome of variations in the effective distance from a channel, together with the effects of bed level changes on over-bank flow magnitude and frequency is the creation of a complex mosaic of sedimentation zones within the floodplain and along the cut-off channel in-fills. Application of these research techniques shows that dendogeomorphic analysis may provide a good way of measuring sedimentation where trees are available, while coring and radionuclide analyses reliably provide information on overall sediment deposition over multi-year periods rather than for a specific year.

The potential for using a geopedological approach to evaluate sedimentation rates on river floodplains was illustrated in another recent study, performed by Saint-Laurent *et al.* (2008). They investigated the relationship between sedimentation and pedogenic processes by monitoring the sedimentological characteristics (layer texture, thickness and microstructure) of floodplain deposits laid down by periodic floods combined with radiocarbon dating (^{14}C) and isotopic methods (^{210}Pb, ^{226}Rd) to establish the ages of the sediments. This enabled them to infer medium-term sedimentation rates along the floodplains based on the degree of soil-development – a pedogenetic approach. This approach also defines short-term deposition rates in areas where the deposition rate exceeds 10 mm/yr.

Hupp *et al.* (2008) carried out a study to measure sedimentation in a forested bottomland over a three-year period using clay pads as artificial stratigraphic markers. They constructed 20 transects across the study area and determined sediment deposition rate, texture, bulk density, and loss of ignition near and above the marked layers. Although the applicability of the results of this research is limited to representing local-scale sedimentation patterns distinctive of forestlands, the methods could be transferred to measure single-year sediment deposition rates in any floodplain environment. Wren *et al.* (2008) reconstructed the history of vertical sediment accretion in an ox-bow lake on the Mississippi River's floodplain based on sedimentation rates determined from ^{14}C, ^{210}Pb and ^{137}Cs measurements made on selected sediment fractions. This study not only established the long-term rate of sediment accumulation but also the way that shorter-term variability in deposition rate was related to migration of the primary channel migration and changes in adjacent land use.

Day *et al.* (2008) also related deposition rates to channel migration, carrying out studies on the lowland, meandering Fly River in Papua New Guinea. The spatial pattern of deposition was recorded through coring, with copper used as a tracer material and related to main-channel and tributary discharges. However, measurements of discharge were undertaken only in the channel and adjacent floodplain, meaning that the results can only really be taken to represent in-channel sedimentation and, at best deposition on the natural levees - not across the floodplain as a whole. This technique is only suitable to investigate floodplain building through lateral accumulation.

A project undertaken by the Irrigation Support Project for Asia and the Near East (ISPAN 1995) focused on improvement of basic knowledge concerning sedimentation processes on the floodplains of the Jamuna-Brahmaputra River in Bangladesh. The project used hydrolological records and measured the depth of radiocesium (^{137}Cs) below the floodplain surface to estimate the thickness of the sediment layer deposited during the approximately 50 years since nuclear testing ceased. This method is useful to measure the long-term sediment accumulation (from 1950s to date), but it is unsuitable to investigate current deposition rates for individual years. This is significant because the floodplain has effectively been changed by both natural and human activities, so that historical rates may not provide a sound basis from which to predict future behaviour.

Walling and He (1998) conducted the same kind of study on five British lowland rivers, using bomb-derived ^{137}Cs for documenting rates and spatial variability of overbank sedimentation. The results show that there is significant spatial variability of lateral accretion although no evidence was found for trend in the downstream directions. This might be because the longitudinal extent of the surveyed reaches was relatively short. Given this, my opinion is that there is a need for further studies on a large braided river that extend along a substantial reach in order to generate the data necessary to support firm conclusions on long-stream trends in sedimentation.

In another project, Walling (1999) examined the impact of land use on catchment erosion and sediment yields from river basins using sediment fingerprinting techniques based on environmental radionuclides, such as caesium^{137} and Pb^{210}. His findings indicate that environmental problems within a river basin may result from sediment storage where sediment-associated pollutants accumulate in sediment sinks through over-bank sedimentation. This is a problem along rivers, which receive sediment and pollutants from industrial effluents and mine waste. In the context of soil pollution and fertility, other metal and non-metal organic and inorganic properties should be measured to draw clear conclusions concerning the environmental and public health issues posed by the deposition of contaminated sediments on UK floodplains due to accumulation of sediments contaminated by lead, cadmium and zinc (Macklin *et al.*, 2006 and Hudson-Edwards *et al.*, 2008). A Similar type of study was carried out by Žák *et al.*(2009) in the Litavka River of Czech Republic and measured the fluxes of heavy metals from a highly polluted watershed during flood events, which is very important to measure the spatial and temporal extent of sediment accumulation.

In the USA, Pease *et al.* (2007) and Lecce *et al.*(2008) investigated mercury contamination of active channel sediment and floodplain deposits resulting from historic gold mining at Gold Hill, North Carolina. Their results suggest that vertical trends in mercury and other trace metals can be useful for interpreting rates of historic floodplain sedimentation. Owens *et al.* (1999) also used sediment core data to measure the concentration of the environmental radionuclides Cs^{137} and unsupported Pb^{210} for providing information on historical changes in rates of over-bank sedimentation and sediment sources. They argued that this method can also be used to estimate the sediment fluxes and to predict impact of potential future changes in land use and climate. Marriott (1996) took a different approach to investigating rates of floodplain deposition based on a theoretical analysis coupled with tests of the theory using flume experiments rather than field measurements. The aim was to incorporate a theoretically sound model for measuring sediment deposition on the floodplain into the simulation model for alluvial architecture, which is derived by Crane (1982). A textural analysis of the flood deposits in the flume was performed, based on numerical models for overbank deposition previously developed by James (1985) and Pizzuto (1987). The results suggest that the rate of overbank deposition and mean grain sizes of the deposited sediment (D_{50}) vary according to the distance from the channel.

Asselman and Wijngaarden (2002) examined overbank sedimentation rate using a one-dimensional model based on Chen's (1975) procedure to estimate sedimentation in settling tanks as a function of the trapping efficiency of the tank. Chen (1975) hypothesised that sediment is spread across the floodplain by convection rather than by diffusion (as assumed in many older models). The silt-one Dimensional Model is used to represent this hypothesis. In Asselman and Wijngaarden's study, daily discharge and observed suspended sediment data for a single flood season on the rivers Rhine and

Meuse in Europe were used to estimate the spatially averaged rate of floodplain sediment accumulation based on a sediment budget approach. This provided an overall average rate over an area extending to several square kilometres. The distribution of deposition across the study area was then inferred using Chen's one-dimensional model. While the application of theory and recognition that the processes actually responsible for spreading sediment across the floodplain are convective rather than diffusive are welcome advances over previous models, I would argue that Chen's simple convective model fails to consider all physical factors affecting sedimentation processes on real floodplains. Unlike the floor of Chen's experimental tank, real floodplains are not flat and the authors should also consider the effects of floodplain topography when attempting to understand and explain patterns of flooding and sedimentation.

In summary, while researchers have developed a wide range of techniques to measure sedimentation and sedimentary strata in floodplains (Table 2.1), these techniques have been applied mostly to relatively small rivers and few measurements of floodplain sedimentation have been undertaken on the world's large river systems (Table 2.2).

Overbank flow is highly variable and subject to the unique characteristics of river systems and the rate of flood recurrence, regularity, duration and variation of the water stage (Junk *et al.*, 1989). Large floods contribute more sediment to the floodplain because of high discharge and higher concentrations (Kesel *et al.* 1974, Gupta 1988, Ritter, 1988), but this type of flood can also partially denude the floodplain surface (Nanson, 1986). Recently, Smith and Pérez-Arlucea (2008) conducted a detailed study on the Saskatchewan River (east-central Saskatchewan, Canada) summer flood of 2005 to measure the natural levee deposits. They used a box corer method to detail the character of flood deposits over recent years. In fact, this technique is a combination of the sedigraph and topographic profile models.

According to Schumm and Lichty (1965), floodplain sedimentation rates vary in space and time. A lot of researchers reveal that the rates of sedimentation is a function with the distance from the channel (Figure 2.7) as well as of local topographic and hydraulic variables (Wolman and Leopold, 1957; -

Table 2.1 Major and available techniques used for measuring floodplain sedimentation rates

Techniques	Description	Major Limitations
Marker Beds	Create a datum layer of distinct material (brick dust, fluorescent-dyed sediment, etc.) on the floodplain surface prior to deposition event(s)	▪ Large errors for deposition of <1cm ▪ Risk of removal and/or diffusive mixing of marker bed
Flood Layers	Direct measurement of thickness of sediment layer deposited in a single year	▪ Large errors for deposition of <1cm ▪ Infrequent events ▪ Not representative of mean accretion rate on floodplain
Buried Horizons	Integrated deposition over *in situ* datum surface (soils, peat layers, etc.) of known age (e.g. dated by radiocarbon analysis), pedogenesis analysis of soil	▪ Errors in dating of datum surface ▪ Horizon not laterally isochronous ▪ Single, integrated deposition rate
Mats	Attach a mat (wood, carpet, jute, etc.) to the floodplain surface prior to deposition event(s)	▪ Large errors for deposition of <1cm ▪ Deposition may not reflects rates on surrounding floodplain 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 floodplain surface
Dendro-geomorphology	Tree ring dating of vegetation that has colonized floodplain surface	▪ Difficulty interpreting geomorphological relationships ▪ Temporal spread of individual colony ▪ Single, integrated deposition rate for life of vegetation
Trace Metals	Depth of occurrence of high-levels of trace metals (Pb, As, Cu, etc.) introduced into rivers by mining in the drainage basin at a known time	▪ Not present in all river systems ▪ Single, integrated deposition rate for period since end of mining
^{137}Cs inventory	Particle-reactive tracer introduced into atmosphere by H-bomb testing in 1963-64 (Walling and He, 1992)	▪ Two sources (river sediment, direct atmospheric flux) ▪ Expensive, special equipment needed ▪ Single, integrated deposition rate for period since of atmospheric testing in 1960s
Water sampling/ Current meters	Direct measurement of suspended sediment concentration and water vectors on the floodplain during overbank flow (Mertes, 1994)	▪ Logistically difficult ▪ Spatial and temporal heterogeneity of suspended sediment flux ▪ Bed load transport into and over floodplain is not measured ▪ 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

Sources: FAP19, 1995: 1-4

Table 2.2 Summary of river studies that quantify floodplain sedimentation rates on time scales of 10-10,000 years

River	Measurement Technique	Sediment Accumulation Rate (cm/yr)	Time Period	References
Culm (UK)	Cs inventories	0-0.7	1954-1987	Walling and Bradley (1989)
Ilme (Germany)	Radiocarbon dating	0.03	1400-present	Hagedorn and Rother (1992)
Fyrisan (Sweden)	50 x 50 cm mats	0.0005-0.015	1986	Gretener and Strömquist (1987)
Coon Creek (USA)	Soil Layers	1.5 (6-15)*	1853-1975	Trimble (1983)
Belle Fourche (USA)	Trace metal (As) contamination	0.9-1.5	1876-1978	Marron (1992)
Maluna Creek (Aust)	Cs inventories	0.3	1954-1986	Nanson *et al.* (1992)
Missouri (USA)	Flood layers	50-200	1982	Ritter (1988)
Fly (New Guinea)	Trace metal(Cu) contamination	0-0.2	1981-1990	Higgins (1990), Day *et al.*(1992)
Jamuna (Bangladesh)	Cs inventories/excess penetration	0-4	1954-1994	ISPAN(1995)
Mississippi (USA)	Flood layer	10-84**	1973 flood	Kesel *et al.* (1974)
Amazon (Brazil)	Water sampling/ current meters	290-580***	1987 flood	Mertes (1994)
Brahmaputra -Jamuna (Bangladesh)	Cs and Pb inventories	0.14±0.16	1996-97	Goodbred and Kuehl (1998)
Brahmaputra-Jamuna (Bangladesh)	Cs inventories	1-4	1994	Allison *etal.* (1998)
Brahmaputra-Jamuna (Bangladesh)	200 x 200 cm marker beds	4-5	2007	This research
Brahmaputra-Jamuna (Bangladesh)	200 x 200 cm marker beds	2-3	2008	This research

Source: Modified after ISPAN, 1995:1-5
* Pre-settlement (following anthropogenic denudation of forest cover in drainage basin)
** Natural levee, *** Maximum rates observed on the natural levee at peak flood

Schumm, 1977; Nanson, 1986; Howard,1992; Nanson and Croke, 1992; Asselman and Middelkoop,1995; Walling and He, 1998; Pierce and King, 2008). Though, most studies leads to a reconstruction of past sedimentation rates but it also important to measure contemporary sedimentation. Although these approaches are limited for measuring the deposition rate of a specific year, they provide useful data on the long-term accumulation rate. Lambert and Walling (1987) used Astroturf as a combination device to measure short-term overbank sediment deposition rate of the River Culm, Devon, UK.

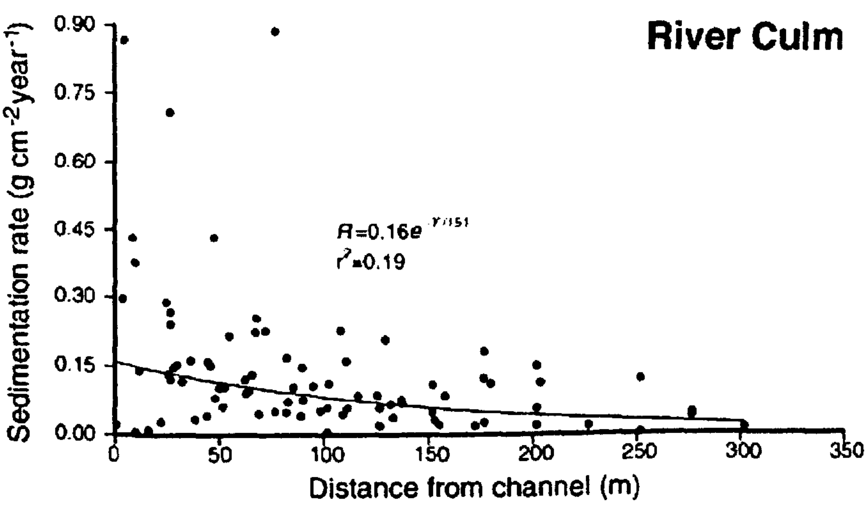


Figure 2.7 Relationship between sedimentation rate and distance from the river channel (Source: Walling and He, 1998: 214)

After that, a good number of researches have employed similar artificial Astroturf mats and marker beds to quantify floodplain sedimentation rates and to determine grain size distributions of the deposited sediment (Walling and Bradley, 1989; Asselman and Middelkoop, 1995; Simm, 1995; Nicholas and Walling, 1996). Even, to measure the sedimentation rate of single year flood event over the floodplain sediment traps methods are significant (Asselman and Middelkoop, 1995; ISPAN, 1995; Smith and Pérez-Arlucea, 2008; Pierce and King, 2008). Therefore, the present research presented in this thesis uses marker bed to measure the current year sediment deposition. This technique is suitable when measuring sedimentation rates of a few millimeters to a few centimeters. Moreover, this technique is more cost-effective and less time-consuming than many of the alternatives. Above all its application is feasible in a developing nation like Bangladesh.

2.4 Floodplain sedimentation in Bangladesh: A general review

Sedimentation in Bangladesh is mainly controlled by the Ganges-Brahmaputra-Meghna (GBM) fluvial system due to its large geographical extent, which encompasses 80% of the land area of the nation. As noted in chapter 1, the contrasting morphologies of the major rivers, variability in their sediment loads, and the presence of a very large number of tributary and distributaries channels (approximately 230) interact to create different topographies and elevations in the floodplains of Bangladesh. Research has shown that floodplain environments in Bangladesh vary considerably depending on the nature of inundation, characteristics of the bounding rivers, floodplain elevation relative to the channel and the presence of off-takes and artificial embankments. All of this ultimately affects the quantity and character of sediment entering the floodplain (Alam *et al.* 1990).

A vast amount of sediment is delivered to the floodplain of Bangladesh due to denudation in the catchment upstreams, and of which 90% of the catchment of three great river system of GBM (Ganges, Brahmaputra and Meghna) lies outside the boundaries of the country (Best *et al.*,2007). Every year, the Ganges and Brahmaputra Rivers in Bangladesh transport 316 and 721 million t of sediment, respectively. Of which, total 525 million ts (51%) are delivered to the coastal area of Bangladesh and remaining 289 (28%) and 223(21%) million t are deposited on the floodplains and within these rivers (Islam *et al.*,1999). Individually, the Brahmaputra-Jamuna River contributes 51% of the water discharge and 38% of the sediment yield to the Padma River (Schumm and Winkley, 1994), although FAP24(1996a) estimate these percentage contribution to the Padma River at 66% and 65% for the water and sediment discharge, respectively. Sarker (1996) study presents the annual average sediment load of the Brahmaputra-Jamuna River at 590 m t per year and of which, 34% of the total load contributing as sand fraction. Although, these figures differ from each other one comment might be drawn from them that particularly in Bangladesh, the Brahmaputra-Jamuna River contributes the higher portion of discharge and sediment load to the Padma River. In another study, Islam *et al.* (2001) estimated the suspended sediment concentration of the Ganges and Brahmaputra River and found the Ganges contributes a higher rate than that in the Brahmaputra. Very recently, a CEGIS (2010) study provides support for the work of Islam *et al.* (2001) (Table 2.3); but this estimation has been done based on the 1994-1996 gauging period.

Table 2.3 Comparative estimates of sediment load among three major Rivers

Period of gauging	Type of sediment	Brahmaputra-Jamuna	Ganges	Padma
	$S_{Swash\ load}$(m t/yr)	277	558	721
1994-1996	$S_{Susp.\ bed}$ (m t/yr)	125	76	227
	$S_{S.\ total}$ (m t/yr)	402	634	948

Source: CEGIS, 2010 (Note: m=million, tonne= t)

The values of this estimation differ with most of the studies done on the Ganges and Brahmaputra river. Based on the available literature, I also argue that sediment load of Brahmaputra-Jamuna will be higher than the Ganges and Padma River.

Wasson (2003) also presented a detailed study on the wider scale sediment budget of the Ganges-Brahmaputra catchments based on published available records in order to present an overview. This research revealed that the Himalaya are the primary source of sediment entering the catchments of the Brahmaputra and Ganges but suggests that only about 8% of this river sediment is actually deposited on floodplains in Bangladesh. This result challenges the earlier finding of Milliman and Syvitski (1992), who concluded that more than 40% of sediment entering Bangladesh was stored in the floodplain, while less than 40% was discharged to the Bay of Bengal. The fact is that there is a lack of empirical evidence to support of these assertions because most field studies and routine measurements of sediment fluxes are limited to the river channels. Thus, their utility constructs a reliable sediment budget for the river that includes floodplain storage.

During the summer monsoon (May-September), high discharge of the three main rivers coming from upstream (supplied mainly from the Himalayan snowmelt and catchment rainfall runoff and localized heavy rainfall), which are the main causes of flooding in the Bangladesh. A study undertaken by MPO (1987) to monitor the flooding extent in Bangladesh found that about 18% of the land area of Bangladesh is inundated by the three-river system during a normal flood, while 54% is inundated by a large flood and 70% of the land area is inundated by a mega-catastrophic flood. The flow and sediment regimes of these rivers have significant effects on the adjacent floodplains. Numerous studies have presented data on the annual water and sediment discharges of the main rivers in Bangladesh (Table2.4), but there is no clear consensus on the figures. Recently, Best *et al.* (2007) compiled a chapter on the Brahmaputra-Jamuna River in Bangladesh that provides an up to date synthesis on the geomorphology and sedimentology of the river and their importance to riverine Bangladesh.

Table 2.4 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 t/yr)			
		Coleman (1969)	MPO (1987)	CBJET (1991)	RSP (1994)
Brahmaputra-Jamuna	19,600	608	387	499	586
Ganges	11,000	479	212	196	549
Meghna	4,800	13	-	-	-

Source: ISPAN, 1995:1-8

Only a few studies specifically demonstrate floodplain sedimentation rates of the Brahmaputra-Jamuna River in Bangladesh. For example, Allison *et al.* (1998) used ^{137}Cs approaches to measure the floodplain sedimentation rate of the Brahmaputra-Jamuna River in Bangladesh. The results suggest that ^{137}Cs accumulation rates decrease exponentially away from the channel, from >4 cm yr^{-1} on the natural levees to <1 cm yr^{-1} within a few tens of kilometres basin ward. The key factors controlling sedimentation were identified as the proximity to distributary channels, local topography, and interannual variability of the flood pulse. The results indicate that an average of 23 m t yr^{-1} of sediment are sequestered in this section of the flood plain. A similar type of study conducted by Goodbred and Kuehl (1998) on the Ganges-Brahmaputra delta found the sediment deposition rate to vary 0.14±016 cm yr^{-1} on the active Brahmaputra-Jamuna floodplain.

Despite the past studies of sediment dynamics and sedimentation along various rivers in Bangladesh, there is no accurate, quantitative information on the floodplain sedimentation, which is not routinely studied or monitored within any floodplain in Bangladesh. There have only been some short-term studies of floodplain sedimentation that have been performed in Bangladesh by FAP 19 (1995) and FAP 24 (1996) on the left bank floodplain of the Brahmaputra-Jamuna for a single flood season. They found the average sedimentation rate to be 1cm yr^{-1} for the young floodplain but 2-4cm yr^{-1} for the active floodplain. However, in considering these measured rates it must be borne in mind that the technique used (artificial marker beds) limits its ability to quantify the exact sediment deposition thickness while the low monsoon runoff in their particular study year severely constrained the extent of floodplain inundation in that particular site.

Another study carried out by Whitton *et al.* (1988) recorded sediment deposition in deep-water paddy land on the Jamuna floodplain. This research considered only sedimentation associated with one specific crop, deep-water paddy, though it raised questions about shallow-water paddy as well as some other types of vegetation (*Imperata cylindrica*) which are also known to be effective in trapping sediments. Although, Whitton's (1988) study was focused on the biological aspects of sedimentation rather than geomorphological ones, it also indicated the need for further research on interactions between vegetation and sediment on floodplains.

2.5 Role of vegetation in sedimentation

River floodplains are some of the most diverse and complex ecosystems on the earth and floodplain vegetation is one of the most important elements of natural systems. Vegetation is not only a vital part of the floodplain food web; it also provides habitat, shading, water quality benefits and erosion protection and sediment deposition to the floodplain during extreme events. As hinted at in the previous section, it is also know that vegetation interacts with processes of flow resistance and fluvial sediment transport to affect patterns of floodplain growth and evolution. It is not, therefore, surprising that increasing numbers of studies have been performed to identify, measure, and classify vegetation in floodplains and riparian corridors.

A great deal of sound theoretical and empirical work on vegetation, flow resistance and subsequent effects on geomorphic processes involving sediment erosion and deposition has been undertaken by, amongst others, Kouwen(1970), Hickin (1984), Thorne (1990), Friedman *et al.* (1996) and Puigdefábregas (2005). One thing that is generally agreed is that the effects of vegetation are complex. With respect to erosion, Trimble (1990) conducted an investigation into the geomorphic effects of vegetation on sediment yield through time and space within the context of a variety of vegetative and non-vegetative surface covers. He showed that sediment yields from areas with shrubby vegetative cover are lower than from areas with no vegetation due to the effects of vegetation cover in reducing the efficacy of processes of soil erosion (Rickson, 1990). Works that are more recent support these early findings. For example, **Xiaoming *et al.* (2007)** support Rickson and Trimble's findings about the role of vegetation cover in controlling runoff and sediment transport, and extend the results to the impact of forest cover in addition to the shrubby vegetation investigated by the earlier researchers.

Bridge (2003) noted that vegetation influences the erosion and deposition of sediment by wind and water and can play a crucial role in affecting patterns of sedimentation on floodplains. It is now recognized that vegetation is one of the most important factors influencing forms and processes in both the channel and the floodplain (Steiger, *et al.*, 2001 and Gurnell *et al.*, 2008). These studies have addressed the impacts of human interventions in the fluvial system on floodplain and riparian vegetation. More recently, Bombinoa, *et al.* (2008) built on the earlier work to develop an improved understanding of the impacts of check-dam installation on riparian sedimentary structure and vegetation. Their results reveal high coefficients of determination linking vegetation character, species diversity and the fine sediment deposition to dam construction. Vanacker *et al.* (2003) who investigated the effect of woody, grassy and shrubby vegetation in the stabilising active gully systems undertook another relevant study. The results demonstrate that woody vegetation is more effective in anchoring the soil than either grassy or shrubby plant species. This research emphasises the efficacy of root enforcement in reducing erosion potential compared to other effects such as rainfall interception by the canopy or boundary shear stress reduction and sediment trapping by the stems. This is not to say that the effect of vegetation on the erosive of near boundary flows is negligible. For example, Shi *et al.* (2005) evaluated the influence of different kinds of vegetation on velocity and Reynolds-stress profiles and concluded that floodplain vegetation has a significant effect on flow structure and boundary resistance. This research provides a template for further research concerning different species of vegetation and these and other hydraulic parameters .

Very recently, Molina *et al.* (2009) investigated the control of vegetation and topography on sediment deposition and storage in gully beds in a degraded, mountain area in Ecuadorian Andes. The study was based on thorough visual estimation of the ground vegetation cover and sediment yield, considering the ground surface slope derived from digital elevation data. They found high variability in vegetation cover that correlated closely with patterns of sediment deposition and channel stabilization, which suggests that gully-bed vegetation is the most important factor in promoting short-term deposition and gully stabilization.

Important research has been undertaken to study in-channel habitat dynamics and the role of different micro and macrophytes in promoting sediment accumulation in the context of seasonal flow variability (Cotton *et al.*, 2006 and Gurnell, 2007). These investigations mainly concentrated on the small, gravel-bedded rivers rather than large, sand-bedded rivers like those in Bangladesh. Despite this, the methodological approaches indicate the type of work that could be implemented in a large river environment to elucidate the effects of vegetation on sediment processes. From an ecological point of view, floodplain vegetation represents one of the key phenomena that must be examined and understood to support management and restoration of floodplain functions damaged by past engineering and development activities (Gregory *et al.*, 1991 and Petts, 1996). It is also widely acknowledged that vegetation promotes sediment deposition on floodplain through trapping fine particles (Thorne, 1990). As the natural river corridors and floodplain ecosystem have particularly high species diversity an exhaustive studies should be undertaken on the effects of riparian vegetation.

Most of the research has been confined to assessing either the impact of sediment on vegetation or the role of vegetation in controlling erosion and runoff hydraulics. Very few studies have examined the influence of vegetation in sediment trapping. A study was conducted to evaluate the long-term effectiveness and operational problems associated with vegetative filter strips (VFS) by Dillaha *et al.*

(1986) and this demonstrated that VFS performed as a most significant factor on the flow regime of runoff in filtering sediment. A similar type of study was carried out by Dabney *et al.* (1996) on stiff grass hedges and their importance in sediment control. They used strips of switch grass and vetiver gras, eastern gama grass, eulia and fescue and found that vetiver grass and switch grass demonstrated the greatest ability to withstand high flows and almost all sediment coarser than 0.125mm was trapped in front of the strip. Although this research was used to monitor erosion control , it has offered new thinking for in depth research in assessing different types of vegetation in terms of sediment trapping efficiency. Hence, vegetation cover has a great influence on controlling sediment through reducing soil erosion and trapping fine particles (Braskerud, 2001 and Rey, 2003). On the contrary, Temmerman *et al.* (2003) reported pposite scenarios, although there is a large difference in the spatial distribution of vegetation in salt and freshwater bodies, they do not affect spatial sedimentation patterns. Because sedimentation processes is governed by the other hydraulics and geomorphic factors rather than vegetation.

The literature on vegetation and sedimentation demonstrates the importance of vegetation on fluvial geomorphic processes and raises awareness of a number of methodological issues regarding the study of vegetation effects on sedimentation processes. Most of the studies present their findings on the geomorphic effects of vegetation within the wider contexts of ecology and agro-economics, but still there is a paucity of literature on vegetation hedges in measuring the sediment trapping efficiency over the floodplains. Consequently, the above mentioned literatures present the basis for the design of in-depth research on how specific types of vegetation influence sedimentation processes on floodplains, where coarse grain sandy sediment effects largely in agricultural land use like Bangladesh Brahmaputra-Jamuna floodplain. In this context, the present study will concentrate on the effectiveness of sun grass (*Imperata cylindrica)* in trapping sediments of various grain sizes, with a view to establishing whether sun grass may have potential for controlling sedimentation in areas of agricultural land use. In addition, few agricultural crops, which stand during floods (*aman* paddy, jute, sugarcane, *sesbania*) will be monitored to find out sediment trapping efficiency on the floodplains.

2.6 Floodplain land use and sedimentation

Floodplains morphologies, processes and ecologies all over the world have been altered significantly by human activities including, particularly, agriculture and mineral extraction and urbanization. In the light of this, it is not surprising that a great deal of research has been conducted to monitor land use change and its impact on the natural environment. Topics of particular focus have been fluvial responses to land use change, the effect of land use on river habitat dynamics and the impact of changing land use on the floodplain sediment budget.

Geeson and Thornes (1996) assessed geomorphic responses to agricultural land use changes , taking into account climatic variability and the vulnerability of soils and parent materials to erosion as key factors affecting landscape dynamics. Their findings illustrate geomorphic responses to changes in the nature and intensity of land use through space and time. Brierley and Stankoviansky (2003) also supported the view that land use is a primary control on floodplain processes in their editorial notes, citing a wide range of prior publication (Bork, 1989). They placed substantial emphasis on the relative roles of land use change and climatic fluctuations in affecting the geomorphic evolution of agricultural areas at a range of spatio-temporal scales.

Walling (1999) demonstrated the utility of sediment fingerprinting techniques using environmental radionuclide, such as caesium^{137} and lead^{210} to establish a link between land use and sediment yields. This contribution endeavored to spur a rethink of the existing understanding of the relationships between land use change, erosion and sediment yield. Although the study extensively documented the impact of land use change on rates of soil loss and, more particularly, the impact of land clearance and cultivation in increasing erosion rates, the evidence for major impacts on the sediment loads of larger rivers is less clear. A study conducted by Cook (2007) on a floodplain in southern England focused on land use and how EU agro-environmental policy at that time favoured conversion of cropland to grassland with the potential to take up more of particular elements (carbon and phosphorous) and to trap sediment. During floods, it was shown that sediment deposition and nutrient uptake do indeed vary significantly between the arable and non-arable (grass) land uses.

Conversely, Cook and Moorby (1993:56) showed that "land-use change on English floodplains and reclaimed marshes mirrors the national picture, the conversion of meadowland pasture to arable land being associated with 'improved' drainage and levelling of fields for agriculture, communications and flood control".

Catchment-scale land use was monitored annually for nine years by Kuhnle *et al.* (1996) at the Goodwin Creek in north central Mississippi, to evaluate the effect of changes in the area of cultivated land on the catchment sediment budget. During the study period (1982 to 1990), the percentage of cultivated land decreased from 26% to 12%. At the same time, the concentration of fines (<0.062 mm) in runoff measured in Goodwin Creek decreased by 62%, while the concentration of sand (0.062 - 2.0 mm) decreased by 66%, and that of gravel (> 2.0 mm) decreased by 39%. This research established a strong positive correlation between reductions in the proportion of the catchment under cultivation and decreases in the quantity and size of sediment transported in the drainage network.

Very recently, Henshaw (2009) studied the impact of historical land use changes and land management practices on contemporary sediment dynamics in upland catchment, Pontbren, Mid-Wales in the United Kingdom and showed the relationship between hydrological and geomorphological processes. This research demonstrated how the agricultural intensification and grazed, agriculturally improved pastures influences fine grained sediment. The above sections mentioned the processes of land use changes and the impact on land use on fluvial sedimentation. However, it is crucial for Bangladesh perspectives to rethink the impact of fluvial sedimentation on agricultural land use and management, because, in total 80%of the land in Bangladesh is classified as floodplain, where people live and practice agriculture for their livelihood. In addition, the monsoon climate and seasonal flooding that affects the agricultural land use greatly (Brammer, 1999). Consequently, land use virtually depends on flood borne sedimentation processes. It is not surprising that very little research has concentrated on the impact of sedimentation on land use dynamics. For example, Box and Mossa (1999) observed the impacts and problems caused to the aquaculture of fresh water mussels by sedimentation. They observed that due to excessive sedimentation, land use has been changing and numbers of fresh water mussels have declined as a result. However, there is a great debate about this and a degree of ambiguity remains regarding the strength of associations between sediments, and mussels, including whether increased sedimentation is a cause of recent mussel decline. Poole and Downing (2004) investigated the relationship of declining mussel biodiversity to stream-reach and watershed characteristics in an agricultural landscape and found that due to changes of the sedimentary characteristics of the watershed it affects the agricultural land use and other biota. This illustrates that it is necessary to study specific associations such as that between sedimentation rate and mussel productivity before firm conclusions can be drawn. It is also imperative to be aware of proper measures for sampling and analyzing the fluvial deposits and to identify the sediment sources, in order to evaluate relationships effectively between the rate of accretion of fluvial sediments, land use change and the growth and health of mussels. It is revealed from the two studies that sedimentation has a great influence on land use.

Wasson (2003) studied the suspended sediment budget for the Ganga–Brahmaputra catchment and found a significant portion of river sediment deposited on Bangladeshi floodplains (Figure 2.8) through annual overbank flood and demonstrated that the relationship between land use, erosion, and sedimentation is not clear, despite many decades of research.

The literature encountered in this review mainly focuses on the response of fluvial and geomorphological processes to changes in land use rather than exploring the effects of sedimentation on land use, which has been largely ignored to date. However, what the studies reviewed here have established is that contemporary floodplain land use is currently of concern due to a wide range of negative impacts on a variety of floodplain functions. It emerges that there is a need to develop sustainable agro-environmental policies and practices, which inevitably leads to adaptive management owing to the dynamic nature of the floodplain environment. As floodplain dynamics are led by sediment deposition and reworking in particularly the large river Brahmaputra-Jamuna floodplain in Bangladesh, this therefore highlights the need for a comprehensive study of sedimentation impacts on agricultural land use dynamics in a large river floodplain, as proposed and performed (in particularly the Brahmaputra-Jamuna floodplain in Bangladesh) in the present research project.

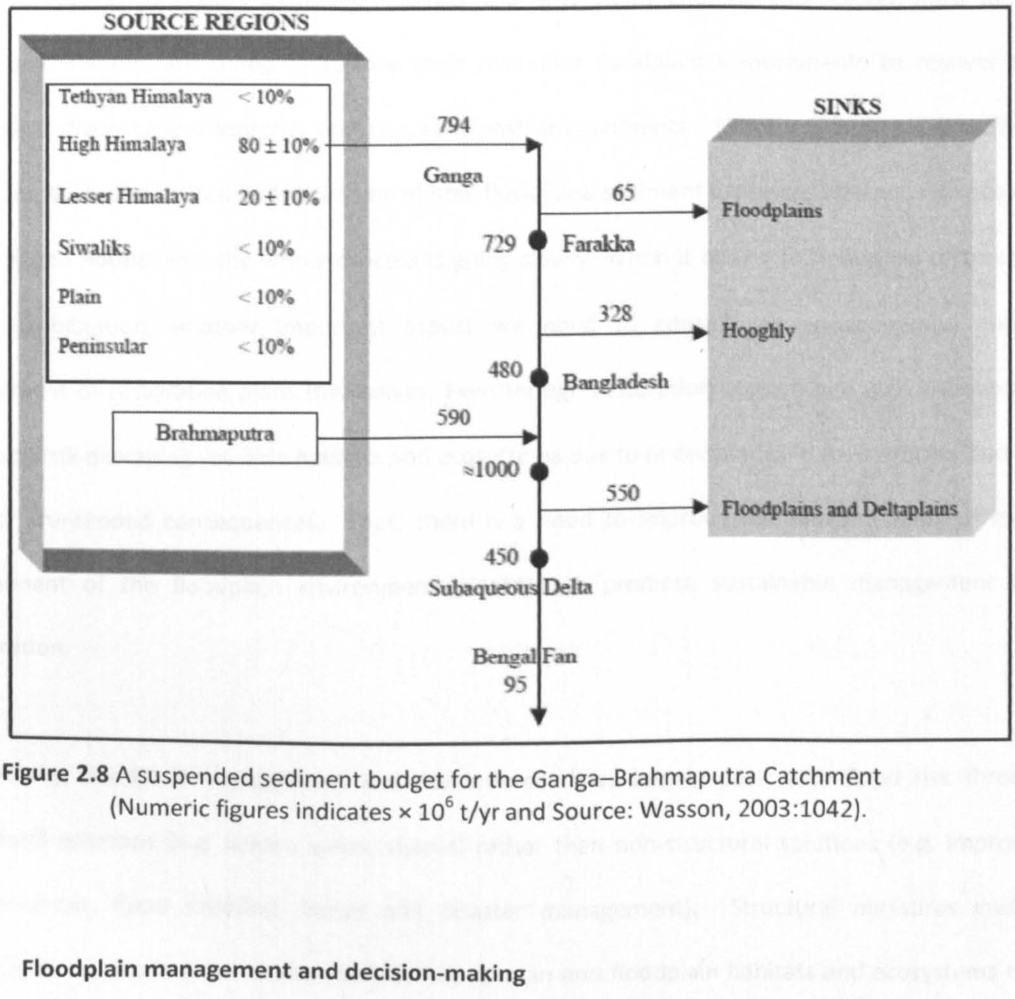


Figure 2.8 A suspended sediment budget for the Ganga–Brahmaputra Catchment (Numeric figures indicates × 10^6 t/yr and Source: Wasson, 2003:1042).

2.7 Floodplain management and decision-making

Floodplains are an important part of the riverscape and have bountiful natural resources. However, despite the numerous planning, management, conservation, and restoration issues on floodplains, the number of studies related to decision-making in the context of sustainable floodplain management and development is still very limited (Naveh, 2007).

Brookes (1996) demonstrated practical approaches for floodplain restoration and management but pointed out both physical (catchment influences) and human (political, economic, lack of scientific knowledge) constraints to large-scale floodplain restoration. In the developed world, contemporary floodplain landscapes are studied as the outcome of anthropogenic influences on fluvial processes and landforms that have been operating for decades or centuries. During this period, people have managed rivers and floodplains for their own interest and until recently, paid little attention to soundly managing the agricultural land use of the floodplain. It would take decades or centuries for fluvial processes to restore degraded habitats and ecosystems and, for this reason, most of the developed nations are trying to restore their river and floodplain environments to recover lost ecological diversity and integrity and re-create past environments. However, due to a paucity of base-line data, and limited understanding of how fluvial and sediment processes interact with ecology in managed floodplains, the whole process is going slowly. When it comes to floodplain restoration and rehabilitation, another important aspect we need to consider is environmental impact assessment of restoration plans themselves. Even though restoration projects are well intentioned, they still risk damaging valuable habitats and ecosystems due to uncertainties in their efficacy and the law of unintended consequences. Thus, there is a need to improve our understanding of every component of the floodplain environment in order to promote sustainable management and restoration.

Historically, floodplain management and development have largely dealt with flood risk through structural solutions (e.g. levees, weirs, sluices) rather than non-structural solutions (e.g. improved preparedness, flood proofing, better and disaster management). Structural measures involve significant environmental impacts on aquatic, riparian and floodplain habitats and ecosystems that can be minimised but not entirely avoided (Werritty, 2006; Thorne *et al.* 2007). Inevitably, a balance must be struck between the needs of the people and the needs of nature in flood management and this over-arches all aspects of floodplain management.

Nijland (2005) carried out an investigation of sustainable development in floodplains and emphasized the need for catchment-scale cooperation to address issues common to multiple floodplains in trans-boundary Rivers. This project was performed for the River Rhine and involved cooperation between Germany and the Netherlands. Unfortunately, trans-boundary cooperation is very difficult for Bangladesh because there is great debate concerning management and sharing of water between India and Bangladesh within the catchments of the Ganges and Brahmaputra Rivers.

Politics are by no means the only human dimension to floodplain management. Morris-Oswald and Sinclair (2005) included socio-cultural values including customs, norms, beliefs and the technologies of local people, which have evolved through interactions with the physical environment, in considering floodplain management and flood mitigation activities. Simonovic and Akter (2006) undertook a similar study through participatory approaches involving local stakeholders taking decisions on floodplain management. Sultana (2008) used this technique in Bangladesh at a community level in promoting local decision making in floodplain resource management. The context for Sultana's approach is that, in Bangladesh, rural populations are dependent on floodplain resources but are faced with inadequate governmental support to manage these resources. It follows that local people can play a key role in implementing and overseeing management decisions and actions. However, stakeholder participation is only possible with relatively small number of stakeholders. Where there are large numbers of stakeholders, other approaches must be devised to involve them in decision-making.

Islam and Braden *et al.* (2006) proposed sustainable strategies for the bio-economic development of floodplains in Bangladesh, covering both ecological and economic factors. They concentrated on floodplain management policies in Bangladesh, emphasizing the structural changes needed to enhance agricultural production by taking into account the effects of flooding depth and timing on production. Their results demonstrated that the balance between agriculture, fisheries and other land uses might significantly affect the long-term economic productivity of a river floodplain, particularly where subsistence consumption is important to social welfare.

Clearly, rivers and flooding are both assets and liabilities. In terms of liabilities, the threat of disastrous flooding can raise risks to unacceptable levels, especially amongst vulnerable groups of people, leading to loss of life, infrastructure and crops. In terms of assets, thanks to flooding the floodplain has fertile soil and abundant moisture, which gives them enormous productivity for agriculture. In addition, the potential for aquaculture is outstanding through both capture fisheries and fish farming in the floodplain.

Management should attempt to optimise human occupation and use of the floodplain in ways that maximise the benefits while minimising the risks in ways that are sustainable. Floodplain usage is changing due to agricultural intensification necessary to meet the food demands of the increasing and governance structures and applying improved floodplain planning and management approaches based on uptake of new technologies and advanced scientific analyses, based on remotely sensed and field data. The innovative means used to supply the scientific evidence-base and the way that technical information is communicated to stakeholders can be used as guidelines in the context of developing countries. The literatures make it clear that human occupation and activities within floodplains will continue to exacerbate floodplain hazards and adversely affect the geomorphologic evolution of river channels and floodplains. Therefore, both physical and human-induced processes should be taken into account when defining and managing the floodplain.

Winklerprins (1999) carried out a study in Peru on how local, vernacular knowledge of soil attributes can be used as a tool for sustainable land management. This qualitative research highlighted ethnographical views and indigenous classification and descriptions of the soils. It concluded that it was possible that integrating local and scientific knowledge using participatory approaches could make land use management more sustainable. It is becoming accepted that stakeholder participation is a key tool in sustainable planning and management of natural resources, which is now widely practiced considering different aspects and contexts. Interest in participatory research with farmers developed in the 1980s to involve farmers more closely in on-farm research and thus build on their indigenous technical knowledge by encouraging them to sharing agro-ecological knowledge (Cornwall *et al.*, 1994). This approach has been quite effective in rural development compared to others, where lack of mechanised knowledge.

There is a wide range of research undertaken on farmer's agricultural knowledge, which is referred to variously as 'local knowledge', 'indigenous knowledge' and 'vernacular knowledge'. Indigenous knowledge is probably the most popular term and it is portrayed as existing in close and organic harmony with the lives of the people who generated it, while modern knowledge or scientific knowledge thrives on abstract formulation and exists at a distance from the lives of local people (Agrawal, 1995). Therefore, farmer's knowledge integrates with their cultural phenomena and often co-exists well with their economic and religious contexts. Scoones and Thompson (1994) have clarified the methodological approaches to building upon farmer's knowledge and many most researchers suggest that participatory approaches are effective in using indigenous knowledge to promote better agricultural decision-making in developing nations.

researchers suggest that participatory approaches are effective in using indigenous knowledge to promote better agricultural decision-making in developing nations.

For example, a detailed study of how to manage floodplain resources through a participatory approach has recently been conducted in Bangladesh (Sultana *et al.*, 2008). The results show how rural people can improve their livelihoods through making better use of available fish resources through participatory approaches. The method adopted for the study is socio-economical rather than bio-technical. However, it is a comparatively better approach to managing an important floodplain resource. As the rural population of Bangladesh depends on the resources of the floodplain, it follows that sustainable management strategies are needed for land use decision making more generally and in this respect, it is essential to consider floodplain sedimentation as a principal factor. If it is possible to integrate local people's knowledge with scientific knowledge concerning the floodplain form and process then more effective and coherent planning strategies for use of the floodplain should emerge. However, both local and scientific knowledge are subject to uncertainties and, therefore, a Bayesian network could provide the probabilistic approach necessary to account for these uncertainties in farmers' decision-making concerning floodplain land use and cropping patterns in Bangladesh. However, the network would have included both the relevant physical and human parameters.

The literature reviewed here includes examples of multiple approaches to floodplain management but also suggests a lack of research on how farmers can assist in their decision-making concerning cropping and land use management. This type of local decision-making rests on experience and vernacular knowledge, but might be enhanced by access to scientific information on the characteristics and dynamics of floodplain forms and processes, especially those involving flooding and sedimentation. However, decision-making based on improved scientific and technical knowledge would also have to take proper account of the environmental, economic and social perspectives in order to manage the floodplain in an adaptive manner that can be sustainable. Hence, better decisions require in land use either farming or non-farming activities. Thus, Bayesian Network Decision Support Systems provides a good alternative approach in decision-making based on the probabilistic inference of any combination of the states of variables.

2.8 Bayesian Network Decision Support Systems (BNDSS)

Bayesian Networks are becoming an increasingly important area for research and application in the field of Artificial Intelligence. They provide a means to take decisions about the occurrence of facts based on probability functions. Both the human and physical sciences are using Bayesian methods to make inferences based on the past and present probability factors. More specifically, a Bayesian Belief Network (BBN) is a knowledge representation method that emerged from combined work in the areas of artificial intelligence, operations research and decision analysis and that finds applications primarily in probabilistic expert systems (Pearl, 1988). Technically, it is a Directed Acyclic Graph, or DAG (Figure2.9), in which the nodes represent variables and the arcs represent causal or temporal relationships between variables (Heckerman *et al*, 1995).

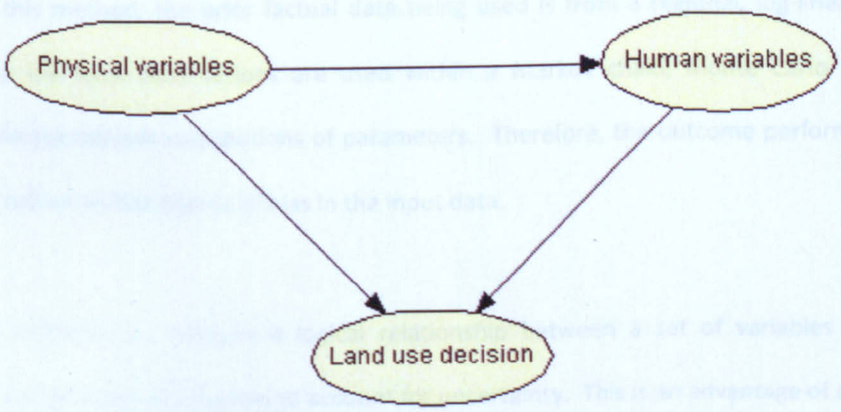


Figure 2.9 Directed Acyclic Graph (DAG) in Bayesian network.

He *et al.* (2007) applied a hierarchical Bayesian model that was developed by Hooten *et al.* (2003) to predict the probability of occurrence for vegetation classification and outlined how the hierarchical Bayesian approach is effective in predicting the historical vegetation distribution with multiple levels of classification. This technique can be used to derive vegetation patterns on the floodplain at different resolutions, but depends on the availability of corresponding functional data at the corresponding scale. Changes to the floodplain occur through time due to both natural evolution, human activities and the impacts appear in the hydrological, hydraulic, and sediment regimes of the floodplains that drive processes of erosion and sediment deposition, and which interact with vegetation succession and land use change. Therefore, if we attempt to use only the current environmental covariates (e.g. terrain, soil, vegetation and land use) to make decisions (on, for example, crop selection) in floodplains where significant changes/interactions have in fact occurred to produce the contemporary situation, this may be insufficient to identify the best choices in a dynamically evolving and responding floodplain. In these situations, decision-making must account for process-form evolution and its interaction with human activities and recognise the trajectory of current changes, through some form of historical reconstruction.

Some investigators are using parametric Bayesian Networks as a functional tool to predict the probability inference of both the natural and human phenomena. Seidou *et al.* (2006) have used linear empirical Bayesian estimation to combine local and regional-scale data in analyzing flood frequency. The application is made with the Generalized Extreme Values (GEV) distribution of flood events. In this method, the prior factual data being used is from a regional, log-linear regression model while the local observations are used within a Markov chain, Monte Carlo algorithm to represent the subsequent distributions of parameters. Therefore, the outcome performance of this approach is reliant on the degree of bias in the input data.

A Bayesian network can produce a logical relationship between a set of variables using causal knowledge and decision preferences to account for uncertainty. This is an advantage of over land-use allocation models and multi-criteria evaluation methods (Jankowski, 1995) but this type of relationships do not explicitly take uncertainty about the future distribution of land-uses into account, which is a major limitation of most existing models and planning support tools for location decisions. Ma *et al.* (2004) proposed a Bayesian Belief Network (BBN) to remedy this limitation. They used a Bayesian belief network as a framework to model knowledge and decision making in land-use planning. Uncertainty was dealt with by specifying causal relationships by means of conditional probabilities. Recently, Ma *et al.* (2007) use this concept more specifically in urban land use planning, to identify the best place for a retail shop under conditions of uncertainty. In this application, they represented uncertainty in future land use development using the uncertainty of conditional probabilities and validated the Bayesian network to predict the probable impacts of future land use on shop location decision making.

Thus, Bayesian networks present a more flexible framework for modelling hydrological, geomorphological and environmental processes than traditional deterministic approaches. For this reason, natural scientists have become increasingly interested in using them to help understand and represent the effects of uncertainties in the causal links between variables. For example, Mount and Stott (2008) recently used a Bayesian Network to investigate suspended concentrations in an Alpine, pro-glacial stream considering discrete, random variables of air temperature, glacier discharge and suspended sediment concentrate. The conditional probability was calculated and explained how the parent and child nodes are linked to each other and what the probable outcome of suspended sedimentation would be given the hydraulics and climatic variables. Palmer and Douglas (2008) analyzed sediment geochemistry using Bayesian statistical model. Their approach allows for incorporation of prior knowledge about the geochemical compositions of the sediment sources and allows for correlation between spatially contiguous samples and the prediction of the sediment's composition at un-sampled locations.

Heckerman (2008) demonstrated the advantages of BNDSS for data analysis, which encodes dependencies among all variables and readily handles situations if some data entries are missing. It can be used to learn causal relationships, and hence can be used to gain understanding about a problem domain and to predict the consequences of interventions. As the BNDSS model has both causal and probabilistic semantics, it is an ideal representation for combining prior knowledge (which often comes in causal form) and data. In addition, Bayesian statistical methods in conjunction with Bayesian networks offer an efficient and principled approach for avoiding the over fitting of data. Thus, the BNDSS approach is found as a novel approach compared to classical and exploratory data analysis techniques (Chapter 7 section 7.2), which can be used for learning techniques for supervised and unsupervised learning through illustrating the graphical-modeling approach using a real world case study like decision making on agricultural land use in Brahmaputra Jamuna floodplain in Bangladesh.

2.9 Conclusion

The preceding sections review the literature on floodplain form, process and management characteristics apparent in different river environments and with different climatic and geologic settings. It emerges that the majority of previous works has focused on either reconstructing deposition sequences of fluvial sediment or predicting sedimentation patterns based on different approaches on relatively small rivers. In contrast, research on large river floodplains has been very limited. In Bangladesh, the river floodplains are the most important component of both the socio-economic and natural environments. Floodplains provide living spaces and livelihoods for millions of people, agricultural production that feeds the nation and underpins the economy and habitats that support diverse ecologies. It is, therefore crucial that the natural resources of Bangladesh's floodplain are managed productively but sustainably and to achieve this it is clearly necessary to undertake integrated and exhaustive research on how local and scientific knowledge can be best utilised in human decision making on agricultural land use. This is particularly true, in terms of understanding the links between floodplain sedimentation, vegetation and land use, and analysing the interaction of sedimentation with agricultural land use.

The research framework for this study has been, therefore, selected to make use of recent methodological advances in ways appropriate to research in a developing nation in an attempt to address some of the more pressing issues yet to be resolved. Specifically, the research is intended to:

i) Compile new and original data on floodplain sedimentation rates and processes,

ii) Investigate the interaction between sedimentation and vegetation,

iii) Develop a Bayesian network that could be used to support improved decision making on agricultural land use by accounting for the effects of sedimentation and farmers' socioeconomic variables.

CHAPTER 3 RESEARCH DESIGN AND FIELD SITE

3.1 Introduction

This chapter introduces an overview of research design, emphasizing the methods employed, the field study components and the study site characteristics. The methodological framework for the research is described in this chapter. However, detailed methods of field data collection and analysis techniques will be further explained in subsequent chapters, as and where these details are relevant to the discourse. The rationale underpinning site selection and the general environmental setting of the study site presented in terms of both physical and human geography.

3.2 Methodological Framework

3.2.1 Methods and data sets

Tables 3.1 outlines the research questions, objectives, required data sets, data acquisition methods and analytical techniques. To answer the research questions floodplain sedimentation, vegetation and land use data sets are require. As there are no available and dependable sources of data on floodplain sedimentation, apart from an in-channel sediment budget for the Brahmaputra-Jamuna River, a unique field investigation had to be performed as the main source of primary data for this research. Hence, this investigation attempts to collect the data on sediment deposition, sediment characteristics, vegetation type and land use based on the two distinct monsoon flood seasons; large flood (*bonna*) in 2007 and normal flood (*barsha*) in 2008.

Figure 3.1 outlines the conceptual framework of the present research through desk and field methods employed, data sets generated and analytical approaches adopted. Further details are provided in the respective analytical chapters (Chapters 4, 5, and 6). The desk-based study incorporated a review of published works. Relationships between sedimentation, vegetation type and land use characteristics are assessed in the context of the broader environmental characteristics of the Brahmaputra-Jamuna River floodplain using exploratory data analysis and bivariate statistical techniques. The field component of the research is subdivided into detailed fieldwork and survey design used for monitoring hydraulic characteristics of flood (depth, duration, velocity), sedimentation processes (marker bed installation and sediment deposition measurement, and particle size analysis), information regarding vegetation type and land use of the study site at the floodplain of Jamuna River in Bangladesh. Details of the field sites are provided in section 3.3. Detailed levelling surveys were conducted during June and October in 2007 and 2008, respectively in order to establish the morphological context for the field site. Hydraulic parameters were measured during the monsoon (July to September in 2007 and 2008) and marker beds were placed in the pre-monsoon period to allow measurement of monsoonal sediment deposition (June 2007 and 2008) along the four transects at the field site. GPS surveys conducted for each sample point (in the form of Easting and Northing values) established the co-ordinates of the transects and the locations of all measurements taken during each survey. Subsequently, a combination of geostatistical and bivariate analytical techniques were applied to the data sets in order to explore the spatial distribution and organisation of sedimentation, vegetation and land use. Detailed surveys were carried out using quadrat surveys of vegetation type in two different flooding areas (riverine and rain-fed) and at three different times (pre-monsoon-May; monsoon-June to September; post-monsoon-October) in both large (*bonna*) in 2007 and normal (*barsha*) in 2008 flood years.

Plot level land use surveys were conducted through structured coding (Appendix-B) for both pre-monsoon and post-monsoon periods in 2007 and 2008, using a base map, which was prepared from a cadastral map (Scale: 16 inches = 1 mile). Further details are provided in chapter 5. Qualitative questionnaire data relating to local people's vernacular knowledge was collected through a semi-structured questionnaire (Appendix-A) and informal group discussion with stakeholders (often farmers) who live and work on the floodplain environments details are presented in chapter 5 and 6. A Bayesian network was developed as a land use decision support system accounting for information on sedimentation and vegetation type. The aim here is to combine objective information gained through scientific investigation along with vernacular knowledge collected from stakeholders to provide the basis for better future land use decision-making. A more detailed explanation of the way the decision support system was developed is provided in Chapter 6 (section 6.4 and 6.5). It was crucial to select the study site carefully because the study site needed to be inundated with river water even when very low floods occurs would be to answer the research questions.

Table 3.1 Outline of research methods

Research Questions	Objectives	Data sets required	Data collection methods	Analytical techniques
1) How was sediment deposition distributed throughout the study area in 2007 and 2008 and what factors are responsible for this distribution (deposition thickness and particle size distribution)?	i) To investigate the characteristics of the floodplain study area; hydraulics (over bank flow velocity, flood depth and duration) and terrain characteristics.	Flood flow velocity, Flood depth, Flood duration Land form elevation	Field survey (during flood) Levelling survey, SRTM data	Exploratory Statistics Bivariate analysis Geostatistical analysis in GIS
	ii) To Examine space and time variations in sedimentation for two monsoon seasons (2007 and 2008).	Sediment deposition-thickness Particle sizes	Marker bed LS-Coulter counter	Exploratory statistics Bivariate analysis Geostatistical analysis in GIS
2a. What is the impact of sedimentation (sand, silt or clay) on agricultural land use and how does rainwater flooding, which is sediment-free, contrast with river flooding?	iii) To assess spatial and temporal variation of agricultural land use patterns	Plot level land use information	Field survey using plot level map through direct observation	Exploratory Statistics Geostatistical and Overlay analysis in GIS
	iv) To contrast the sedimentation characteristics associated with rainwater flooding and river flooding	Sediment deposition-thickness Particle sizes Blue Green Algae	Astroturf LS-Coulter counter Field survey by direct observation and measurement	Exploratory Statistics Bivariate analysis
2b. How does vegetation (e.g. Sun grass - *Imperata cylindrica* (Linn.) (Rauschel, Graminea/Poaceae) act to trap sediment?	v) To document vegetation characteristics; identify how vegetation acts to trap sediment, how different grain sizes are affected by vegetated buffer strips.	Vegetation density Sediment deposition-thickness Particle sizes	Quadrat survey Astroturf LS-Coulter counter	Exploratory Statistics Bivariate analysis
3. How do farmers account for sedimentation when deciding what crop to grow on a plot of land? Could they make better decisions if they had better information on sedimentation?	vi) To document farmers' perceptions on sediment and agricultural land use.	Farmers' vernacular knowledge on soil and agricultural land use, crop selection	Semi structured questionnaire survey, Informal discussion and Direct field observation	Exploratory Statistics Bivariate analysis
4. How do farmers decide on land use more generally and would a Bayesian Network Decision Support System assist them?	vii) To evaluate the effects of sedimentation on human decision-making concerning agricultural land use.	Probability of physical (sedimentation) and farmers crop selection criterion	Conditional probability calculation Using Bayes' theorem	Bayesian Network Decision Support System (BNDSS)

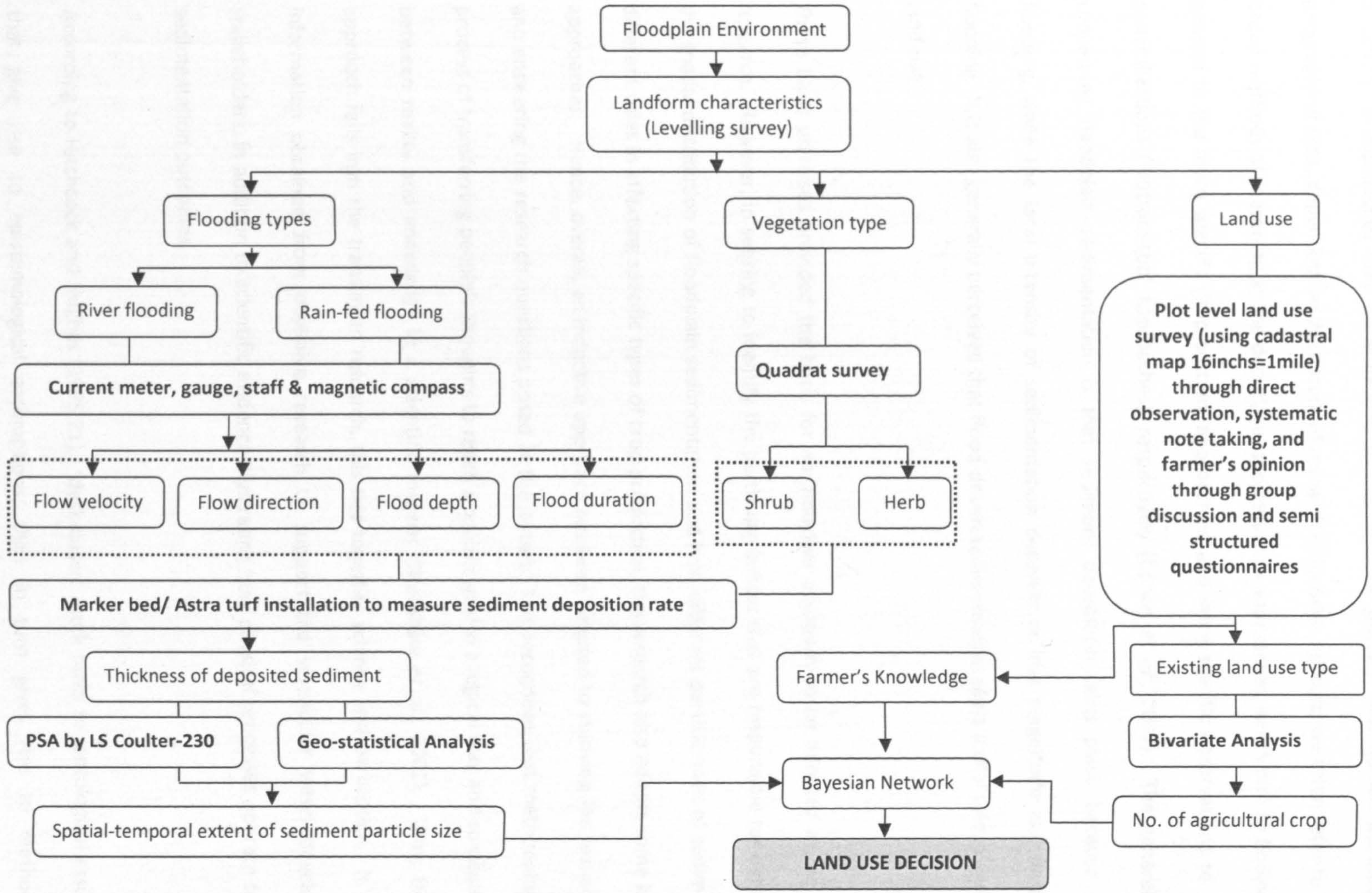


Figure 3.1 Conceptual framework developed for the Brahmaputra-Jamuna Floodplain in Bangladesh to represent interactions between influencing components (Sedimentation, vegetation type and land use) on land use decisions.

3.2.2 Approach adopted in this study

A variety of approaches may be employed to examine the physical and human attributes of a geographical area, depending on the nature of research objectives. In logic, we often refer to the two broad methods of reasoning as the deductive and inductive approaches, which aim to finding more general to the more specific ('top-bottom' approaches) and more specific observations to broader generalizations ('bottom-top' approaches), respectively (Cohen *et al.*, 2007). The general notion concerning *floodplain sedimentation* is that sediment deposition takes place because of river flooding, while the local intensity of sedimentation depends on the magnitude and duration of flooding. It is also generally perceived that flood-driven sedimentation plays a vital role in agricultural land-use.

These basic premises provided the basis for an inductive approach to be adopted in the present research. However, in seeking to identify the particular factors that are responsible for determining the spatial distribution of floodplain sedimentation and how different particle sizes of sediment play different roles in affecting specific types of crop production, the research also adopts some inductive approaches. Hence, overall, an inductive approach has been adapted to studying the research topic and answering the research questions posed at the outset. This recognises that methodology is the process of transferring people's thoughts to reach a specific goal in a logical way and so depicts a link between reality and knowledge in a scientific manner (Bradshaw *et al.*, 2001). Thus, this study approach falls into the translation research, this ties together science and perception. It provides information obtained from objective research to support the vernacular views developed by stakeholders, in addition to scientific evidence illustrating how physical processes operate to deliver sedimentation outcomes.

According to Hitchcock and Hughes (1995:21), 'desk-based work turns to ontological assumptions that give rise to epistemological assumptions; then in turn gives rise to methodological considerations; and these in turn give rise to issues of instrumentation and data collection' (Figure 3.2). In this context, the research reported here involves both explicit and implicit assumptions.

Reviews of the literature on sedimentation processes and floodplain environments provide a synthesis of existing knowledge regarding the specific question of how sediment is distributed over the floodplain and the strengths and weaknesses of measurement techniques by which sedimentation may be investigated (Hakim, 1987).

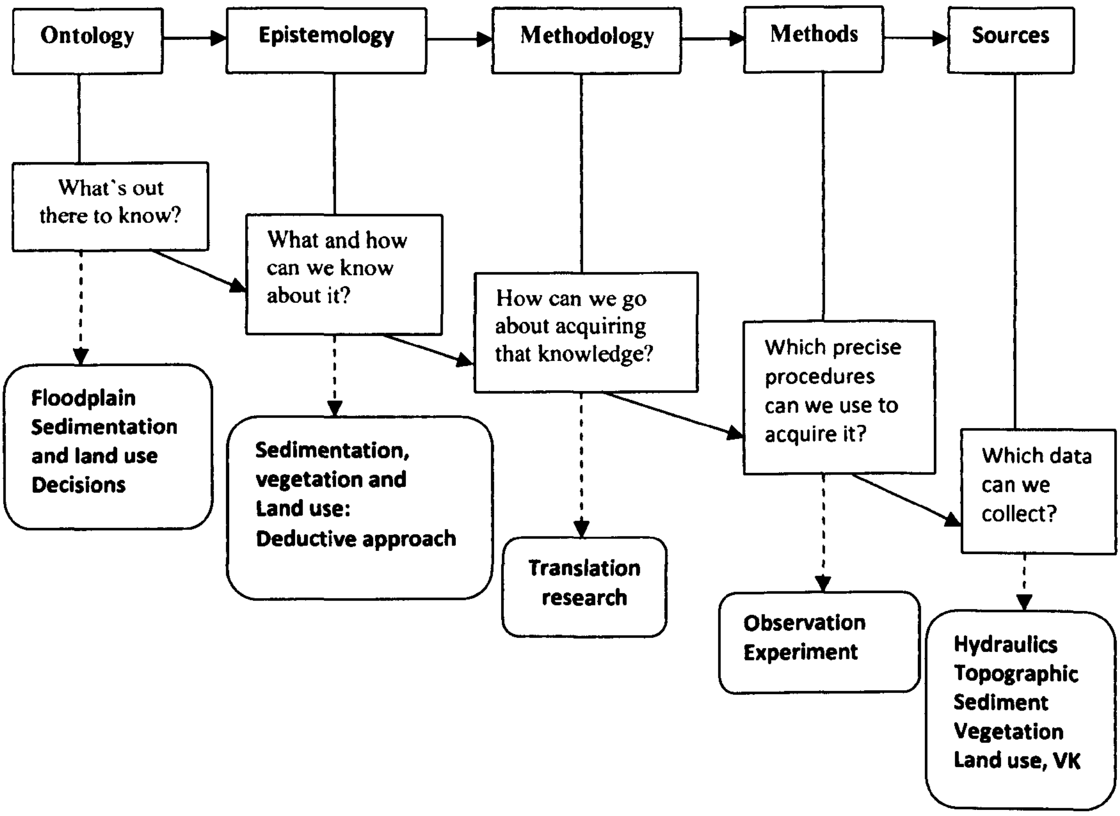


Figure 3.2 Interrelationship between the building blocks of research (Modified after Grix, 2004:66) [Note: 'VK' means farmers' vernacular knowledge about soil and agricultural decision]

In this study, the research objectives and questions have been formulated through literature reviews that represent extensive approaches, while field study components have measured and analysed key parameters by deploying intensive approaches appropriate to the spatial and temporal scales implicit to floodplain sedimentation processes and land use decision making. With respect to spatial scale, transactional sampling surveys were undertaken to organise the sampling sites, with the transects used to measure sediment deposition scale on to extend from the natural levee to the back swamps in multiple locations. In the temporal dimension, parameters were re-sampled during pre-monsoon, monsoon and post monsoon periods in the 2007 and 2008.

Due to practical limitations imposed by the resources available to support doctoral research, the field research focuses on investigation of floodplain sedimentation, vegetation type and land use dynamics within a single floodplain and at the micro scales. In contrast, the desk-based component incorporates a macro scale aspect and considers relationships between the macro-scale attributes of key variables and local features at the micro-scales, providing a wider context for the primary data set.

3.3 Bangladesh: General Background

Bangladesh is located at the intersection of the tropic of cancer and longitude 90^0 east and at the confluence of the three great rivers of the Ganges-Brahmaputra-Meghna (GBM) basin. It has a riverine physical geography and comprises the channels and floodplains of great rivers, together with their numerous tributaries and distributaries. Altogether 230 rivers, including 54 international rivers, flow through the country to form a criss-cross network of drainage systems (Figure 1.3).

Geologically, as a whole Bangladesh is part of the Bengal basin and lies in an active tectonic zone (Brammer, 1996). The Bengal basin is characterized by anticline folds and faults (Mithal, 1968) and comprises ~100,000km^2 of lowland floodplain and delta plain (Goobred and Kuehl, 2000). The Cretaceous Shillong Massif bounds it to the north, a shelf area of the Pre-Cambrian Indian shield bounds it to the west and a folded belt of Tripura to the east (Figure 3.3). The subsurface geology and tectonic features of the Bay of Bengal vary considerably from one area to another. The Brahmaputra-Jamuna river floodplains lie within the seismically active zone of the Bengal Basin (Seijmonsbergen, 1999). The river valley is underlain by Quaternary sediments (fluvial deposits) approximately 200-300 metres thick and consisting of clay, silt, sand and pebbles (O'Malley, 1917; Goswami, 1985). The prevailing sediment is sandy, micaceous and calcareous clay (O' Malley, 1917). The depth of the pre-Cambrian basement rock over which Quaternary sediment lies is about 4 kilometres at Bahadurabad, 6 kilometres at Serajganj and more than 10 kilometres at the confluence of the Ganges-Brahmaputra near Goalunda-Aricha (Gupta,1976; Tappin *et al.*, 1998). The whole country is classified into three broad geological formations. The first is the northern and eastern hills, which consist of tertiary sediments, the second formation makes up the central and western zones, known as *modhupur* clay of *modhupur* and *barind* tracts. The final zone is composed of recent alluvial deposits, which make up the contemporary floodplains (Brammer, 1996). The research study site lies in this zone, featuring recently deposited alluvium that forms unconsolidated floodplain sediments, which occupy almost 80 percent of total area of Bangladesh (Figure3.3).

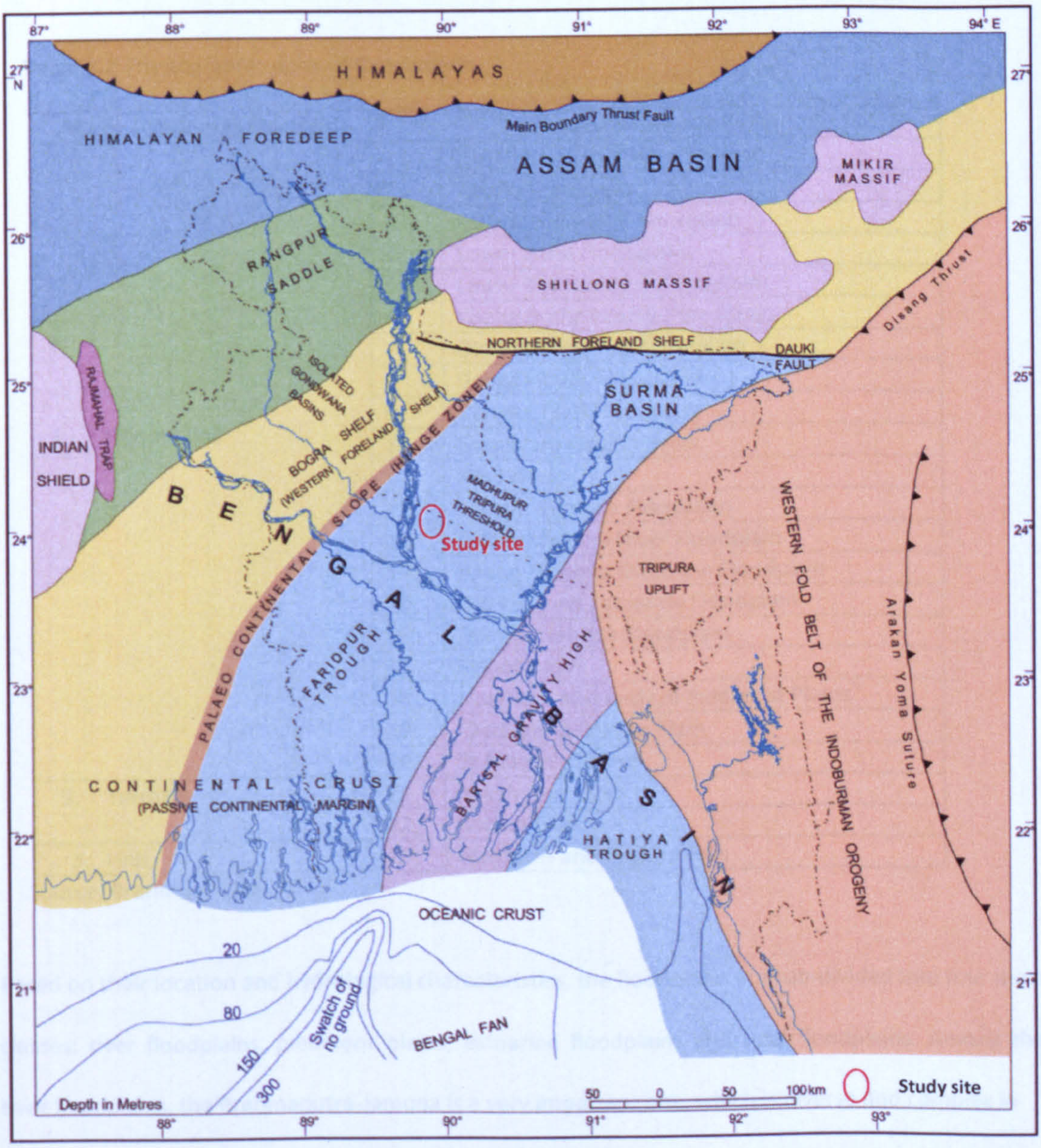


Figure 3.3 The major tectonic framework of the *Bangal* Basin around Bangladesh (Sources: Guha, 1978; Alam *et al.,* 1990; Reimann, 1993)

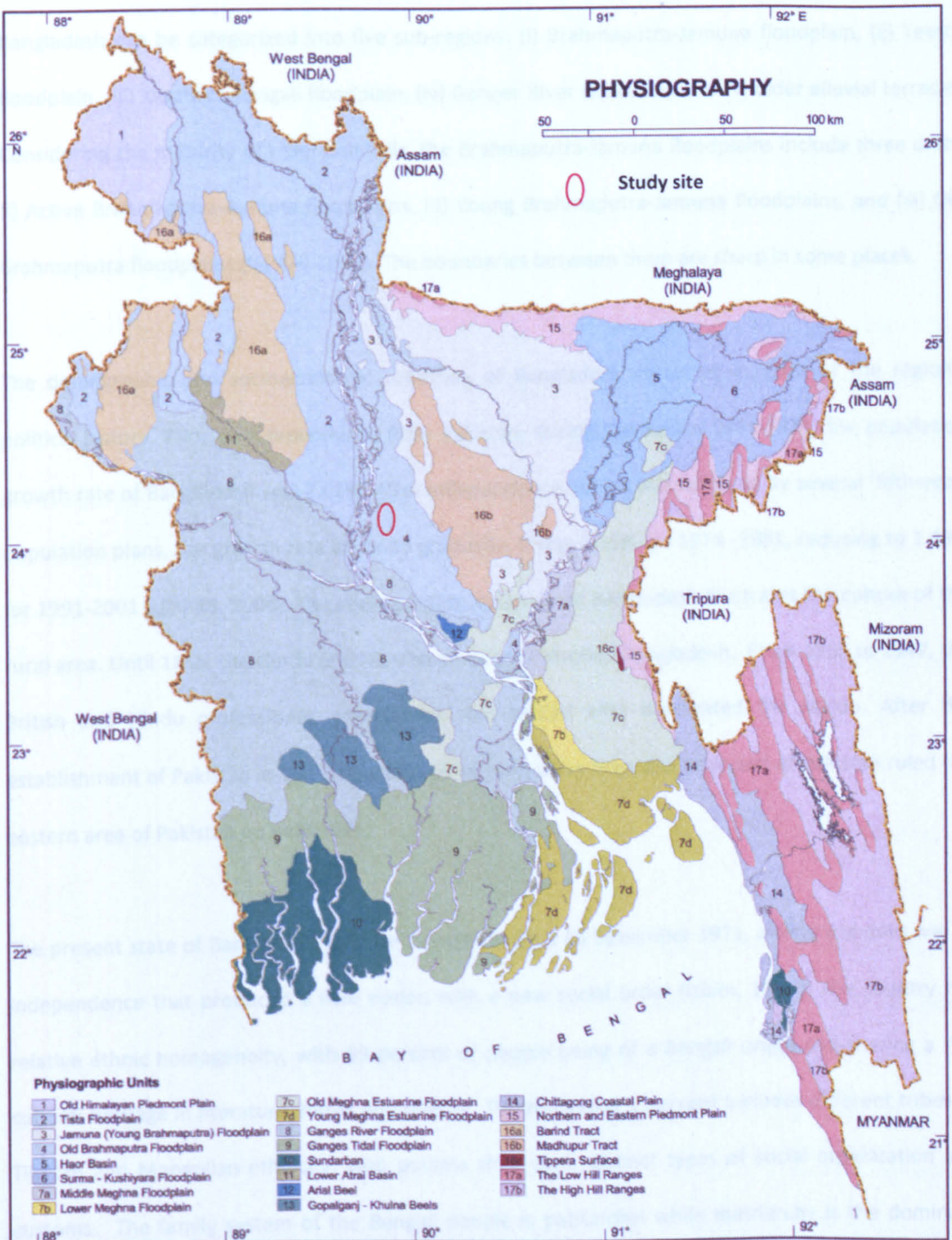
The physiography of Bangladesh is complex. Firstly, the country is divided into three broad distinct units: floodplains (80%), terraces (8%), and tertiary hills (12%). Each of these units displays unique characteristics. Based on these landform characteristics, the country is classified into 24 sub-regions and 54 units (Rashid, 1991). Furthermore, Brammer (1996) considered soil, drainage and hydrological characteristics to classify Bangladesh into 3 broad units with 23 sub-units (Table 3.2 and Figure 3.4). Within this plethora of regions, sub-regions and units, the present study considers only the attributes of the floodplains, as these are relevant to the investigation reported here.

Table 3.2 Physiographic units of Bangladesh

Major Physiographic Units	Physiographic sub-units	
1. Floodplains	1	Old Himalayan Piedmont Plain
	2	Teesta floodplain
	3	Karatoya-Bangali Floodplain
	4	Lower Atrai Floodplain
	5	Lower Purnabhaba Floodplain
	6	Young Brahmaputra Floodplain
	7	Old Brahmaputra Floodplain
	8	Ganges River Floodplain
	9	Ganges Tidal Floodplain
	10	Gopalganj-Khulna Beels
	11	Arial Beel
	12	Middle Meghna Floodplain
	13	Lower Meghna River Floodplain
	14	Young Meghna Estuarine Floodplain
	15	Old Meghna Estuarine Floodplain
	16	Surma-Kusiyara Floodplain
	17	Sylhet Basin
	18	Northern and eastern Piedmont Plains
	19	Chittagong Coastal Plain
	20	St Martin's Island
2. Terraces	21	Madhupur Tract
	22	Barind Tract
3. Hills	23	Northern and Eastern Hills

Source: Brammer, 1996:70

Based on their location and hydrological characteristics, the floodplains are sub-divided into four main classes: river floodplains, piedmont plains, estuarine floodplains and tidal floodplains. Among the river floodplains, the Brahmaputra-Jamuna is a very important one, which is diverse and complex in nature. The seasonal flooding and associated hydrological regime provide the Brahmaputra-Jamuna floodplain with unique characteristics.



Source: Modified From *SRDI,1997; Rashid, 1991; Reimann, 1993*

Figure 3.4 Physiographic units of Bangladesh

Partitioning it based on its geomorphic units, the basin of the Brahmaputra-Jamuna River in Bangladesh can be categorized into five sub-regions: (i) Brahmaputra-Jamuna floodplain, (ii) Teesta floodplain, (iii) Karatoya-Bangali floodplain, (iv) Ganges River floodplain and (v) older alluvial terraces. Considering the maturity of relief and soils, the Brahmaputra-Jamuna floodplains include three units: (i) Active Brahmaputra-Jamuna floodplains, (ii) Young Brahmaputra-Jamuna floodplains, and (iii) Old Brahmaputra floodplains (ISPAN, 1995). The boundaries between them are sharp in some places.

The demographic and socioeconomic condition of Bangladesh varies as a result of the region's political history. Prior to independence from Pakistan, during the period 1961-1971, the population growth rate of Bangladesh was 2.61%. After independence, which was followed by several 'fifth-year' population plans, the growth rate declined gradually. It was 2.35% for 1974 -1981, reducing to 1.48% for 1991-2001 (UNPRB, 2006). The socio-political structure of Bangladesh illustrates the culture of the rural area. Until 1858, the Hindu and Muslim empires controlled Bangladesh. From 1858 to 1947, the British and Hindu professional, commercial, and landed elite dominated the region. After the establishment of Pakistan in 1947, non-Bengali Muslim elites from the west part of Pakistan ruled the eastern area of Pakistan up until 1971.

The present state of Bangladesh became independent on 16 December 1971, after a 9-month war of independence that produced a new nation with a new social order (Islam, 1997). The country has relative ethnic homogeneity, with 99 percent of people being of a Bengali origin and sharing a rich cultural heritage in literature, music and poetry. The remaining 1 percent includes different tribes of Tibetan and Mongolian ethnicity, who possess their own, distinct types of social organization and customs. The family system of the Bengali people is patriarchal while matriarchy is the dominant family system for the tribes. Almost 87 percent of people are considered Muslims with the remaining 13 percent following the Hindu, Buddhist and Christian religions. Patterns of social organization and customs vary widely within the religions. However, kinship is very strong within the family structure. There is strong social stratification within Hindu society, which features different caste categories. In the context of rural and urban systems, Bangladesh had predominantly and historically a rural social system, but now this pattern is changing.

Bangladesh is an agricultural country and approximately 77 percent of its population engaged in farming, with more than 45% living below the poverty line. The principle agricultural crops are rice, jute, wheat, sugarcane and tea, while other important products are pulses, sweet potatoes, oilseeds, tobacco, and various fruits such as Jackfruit, bananas, mangoes and pineapples, which contribute significantly to the Gross Domestic Product (GDP). According to the BBS (2007), the main contributors to Bangladesh's GDP are agriculture (19%), industry (29%) and services (52%), and GDP growth rate is 6%. In the case of the study site, the economy is overwhelmingly agriculturally based (95%). Intensive, subsistence agriculture is the main economic activity and more than 90% of people are living below the poverty line. Poverty in rural areas stems from a lack of education, technical knowledge and good governance, a high rate of unemployment, traditional farming systems, insufficient agricultural subsidies, frequent natural calamities, gender discrimination, the absence of easy access to transport and communications, poor utility services and malnutrition of mothers and children (IUCN, 2005b and Sultana and Thompson, 2008). All of these factors exist in the study area and combine to define it as 'poor' site.

3.4 Field site

The present study was performed on the left bank floodplain of the Jamuna River named *Bara Bannia Mouza (village)* under *Daulatpur Uazila* in *Manikgong,* which is located 5 km away from the main Jamuna channel, and includes a major distributary river, the *Gauge Ghata/ Ghior* River (Figure3.5 and 3.6). The study site is the part of active Jamuna floodplain, because it is known to be subject to floodplain development through channel migration and sediment processes. The area is bounded by relatively smooth boundaries with the main Jamuna River and a distributary, the *Ghior* River. Overbank inundation takes place from the Jamuna and Ghoir/Gauge *Ghata* Rivers during most monsoon seasons. Another distributary, the *Daleswari* River flows to the north at a distance of about 20 km from the study site before joining with the *Ghior* River at *Taraghat* 10 km away from *Manikganj* town to form the *Kaliganga* River. The floodplain of this area mostly formed with stratified sands and silts and comprise with irregular reliefs featuring linear ridges and inter-ridge depressions. The study site is heavily charged with sediment each year by monsoon flood and this has a huge influence on varying hydrology, physiography, soils, microclimates, vegetation and land use (SRDI, 1990). The next section details the rationale of selecting the study site.

3.4.1 Rationale of study site selection

The Brahmaputra-Jamuna is one of the principal river systems in the world in terms of discharge and sediment budget (Thorne *et al.*, 1993, Islam, 2006). Officially, its floodplain is known as the Brahmaputra-Jamuna floodplain because the Brahmaputra River is recognized internationally. However, locally, the main course of the river is familiarly called the Jamuna, with the name Brahmaputra referring to the Old Brahmaputra.

Hence, sometimes Brahmaputra-Jamuna or Jamuna both will be used throughout this research frequently. As stated in the initial chapter, there is a vast body of research work on hydrology and sediment budget that concentrates mainly on the in-channel environment.

Conversely, very little research has been conducted concerning sediment processes that affect the floodplain environment particularly agricultural land use. The most relevant study was performed in 1995, when the flood action plan (FAP19) studied sedimentation on the northern part of Jamuna left bank floodplain. Unfortunately, that year experienced an exceptionally low flood levels, and the FAP study sites were not inundated. Due to this, the study team shifted their efforts to the attached bars (*Chars*) in an attempt to quantify the rate of sediment deposition on the floodplain, which actually limits the ability of the study to provide adequate information about floodplain sedimentation rates and patterns. Considering the experience of the FAP team, it was decided in the present study that a primary criterion for the field site should be that it was in area that is inundated in most years - even when lower than average floods occur. Other study site selection criteria included:

- an absence of flood control embankments along the site,
- an active floodplain without any large ridges,
- a location very close to the Jamuna River,

- a low land area compared to the river upstream,
- an area that inundates by over flow from a distributary and main channel Jamuna, and
- an area which floods even during low monsoon runoff years.

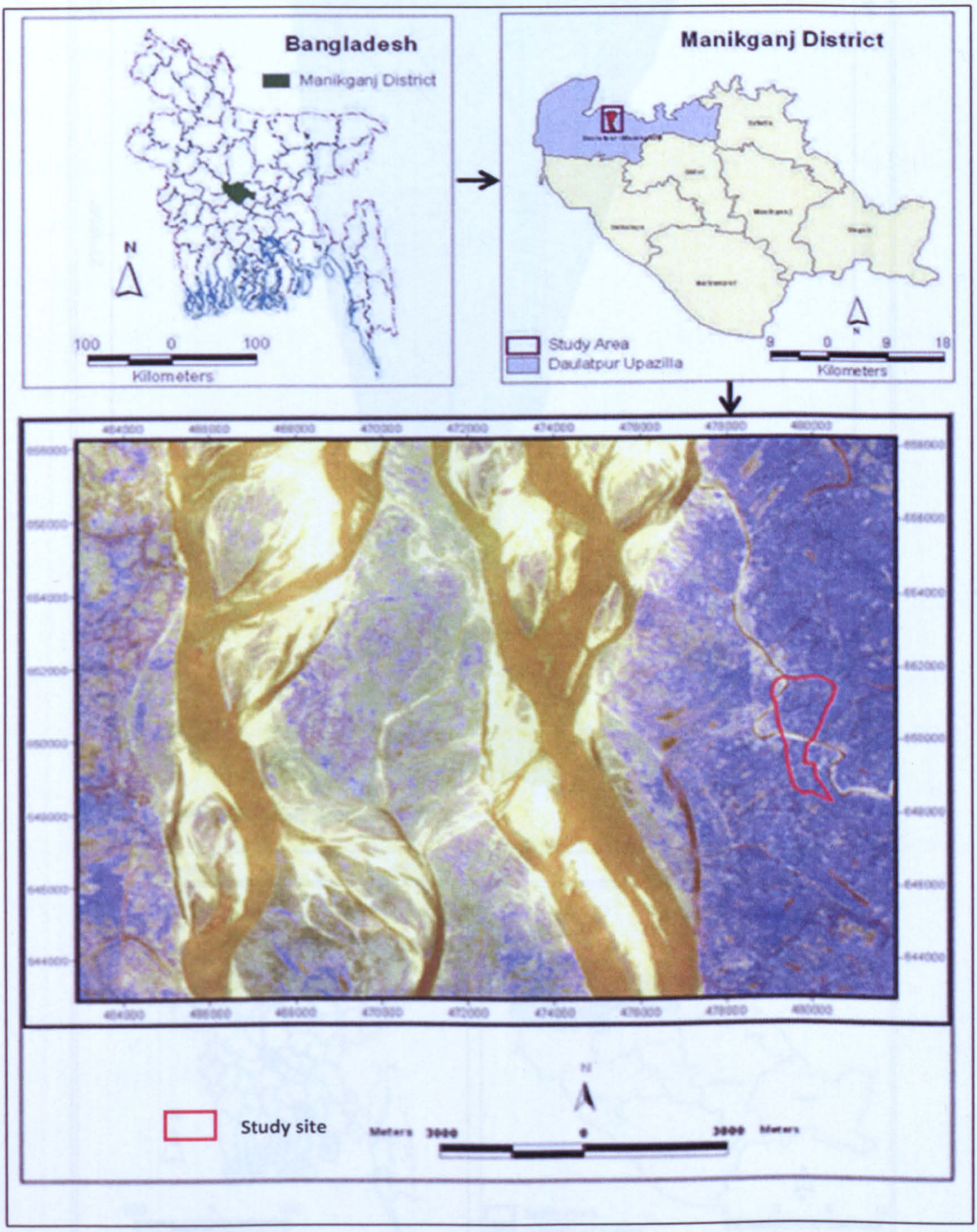


Figure 3.5 The study site location near the Brahmaputra-Jamuna River in Bangladesh

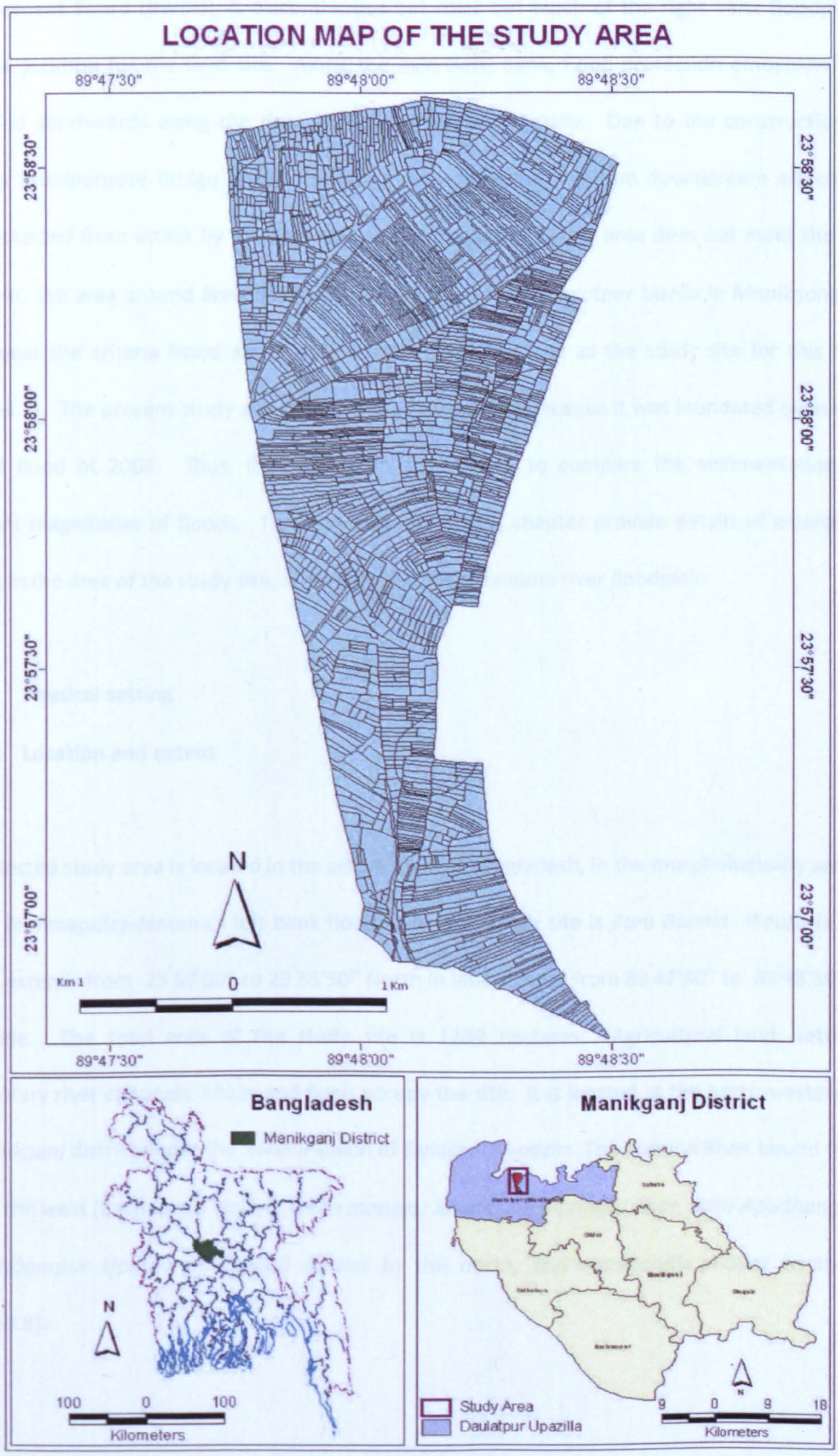


Figure 3.6 Study sites (*Bara Bannia Mouza*-village) under *Daulatpur Upazila* in the *Manikganj* district of Bangladesh

An embankment along the west (right) bank of the Jamuna River built by the Bangladesh Water Development Board (BWDB), is discontinuous but rules out much of the right bank floodplain as a possible location for the field site. Along the east (left) bank, flood protection embankments also extended southwards along the river as far as Nagorpur *Upazila*. Due to the construction of the Jamuna Multipurpose Bridge (JMB), the banks 2km upstream and 2km downstream are controlled and protected from attack by the river and so the floodplain in this area does not meet the criteria. However, the area around *Boro Bania Mouza (village)* under *Daulatpur Uazila* in *Manikgong* district does meet the criteria listed above and hence; it was selected as the study site for this research (Figure3.7). The present study site selection was acceptable because it was inundated even with the normal flood of 2008. Thus, it provided an opportunity to compare the sedimentation of two different magnitudes of floods. The next sections of this chapter provide details of environmental setting in the area of the study site, in the context of the Jamuna river floodplain.

3.4.2 Physical setting

3.4.2.1 Location and extent

The selected study area is located in the central part of Bangladesh, in the morphologically active area of the Brahmaputra-Jamuna's left bank floodplain. The study site is *Baro Bannia mauza* (a village), which extends from 23°57'00" to 23°58'30" North in latitude and from 89°47'30" to 89°48'30" East in longitude. The total area of the study site is 1289 hectares. Agricultural land, settlements, distributary river channels, *khals*, and *beels* occupy the site. It is located at the north-western corner of *Manikganj* district under the *Jianpur* union of *Dalatppur* upazila. The Jamuna River bound the study site to the west (Bachamara Union), three *mauzas; Joinda, Khas-pongtir Char, Boro Apudhanga* to the east, *Nagorpur Upazila* of *Tangail* district to the north, and *Narayandia mauza* to the south (Figure3.8).

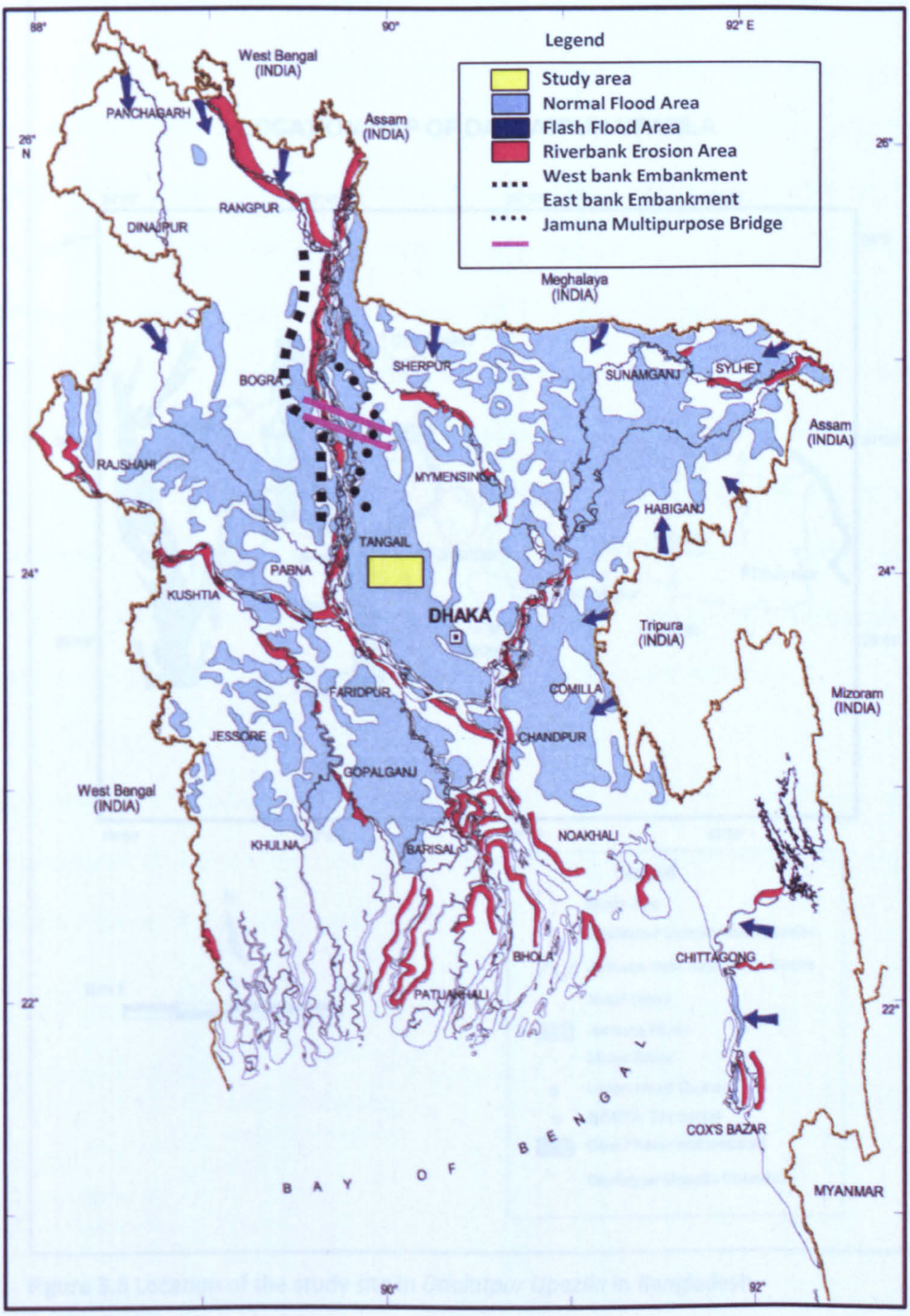


Figure 3.7 Selected study area in relation to embankments along the Jamuna River and the Jamuna multipurpose bridge (Source: modified after BWDB, 2006)

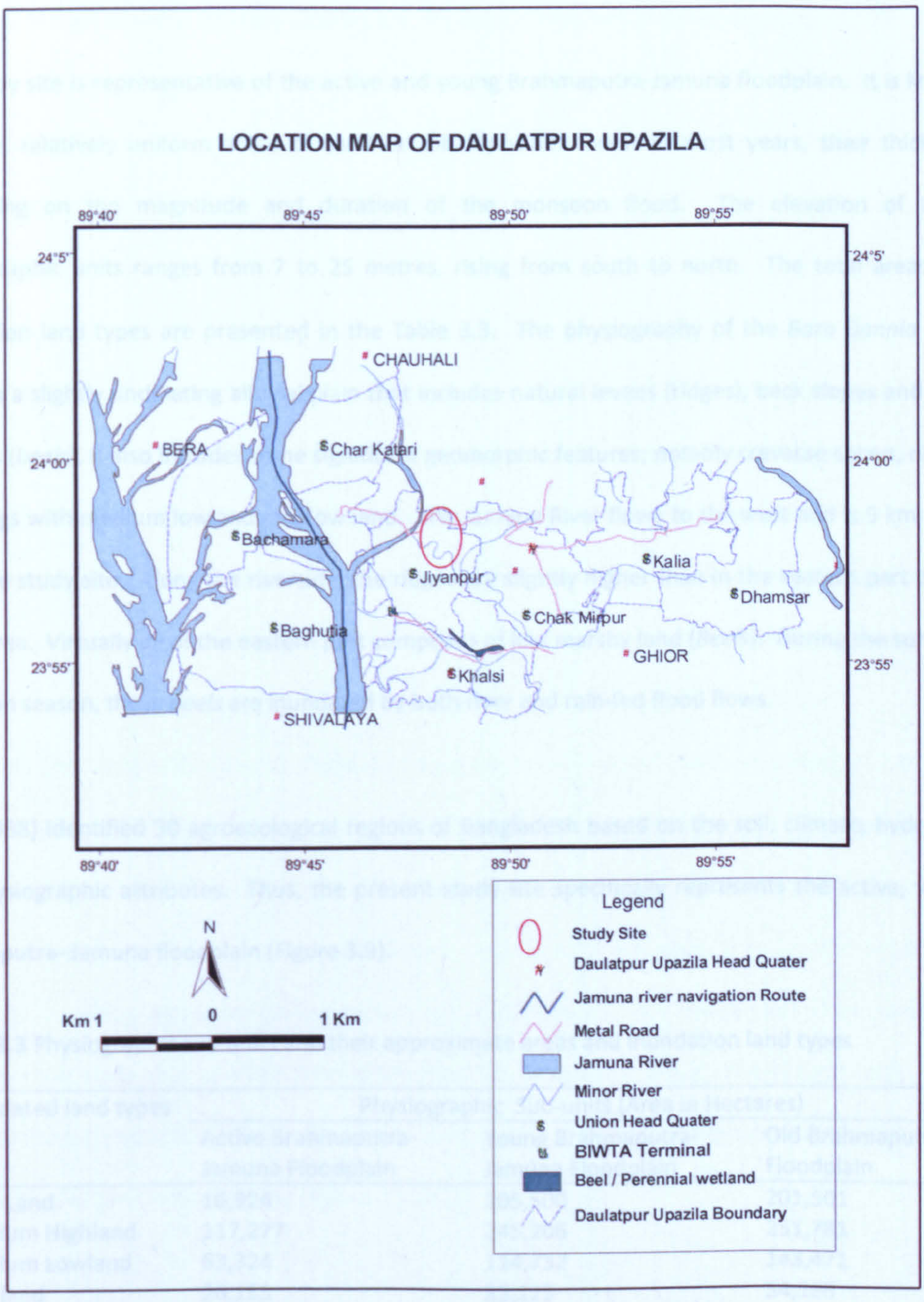


Figure 3.8 Location of the study site in *Daulatpur Upazila* in Bangladesh

3.4.2.2 Physiography

The study site is representative of the active and young Brahmaputra-Jamuna floodplain. It is known as large, relatively uniform areas of sand or silt deposition occur in most years, their thickness depending on the magnitude and duration of the monsoon flood. The elevation of these physiographic units ranges from 7 to 25 metres, rising from south to north. The total areas and inundation land types are presented in the Table 3.3. The physiography of the *Bara Bannia* plain features a slightly undulating alluvial plain that includes natural levees (ridges), back slopes and back swamps (*beels*). It also includes some significant geomorphic features; notably crevasse splays, ridges, clay plugs with medium lowland and low land. The Jamuna River flows to the west and is 5 km away from the study site. Along the riverside, the ridges are slightly higher than in the eastern part of the study area. Virtually all of the eastern part comprises of low marshy land (*Beels*). During the summer monsoon season, these *beels* are inundated by both river and rain-fed flood flows.

FAO (1988) identified 30 agroecological regions of Bangladesh based on the soil, climate, hydrology and physiographic attributes. Thus, the present study site specifically represents the active, young Brahmaputra- Jamuna floodplain (Figure 3.9).

Table 3.3 Physiographic sub units and their approximate areas and inundation land types

Inundated land types	Physiographic Sub-units (Area in Hectares)		
	Active Brahmaputra-Jamuna Floodplain	Young Brahmaputra-Jamuna Floodplain	Old Brahmaputra Floodplain
High Land	16,924	105,500	201,501
Medium Highland	117,277	245,206	251,781
Medium Lowland	63,324	114,732	143,471
Low land	26,155	53,123	54,166
Very low land	0	0	91

Source: LRA, 1988

3.4.2.3 Hydrology

The hydrology of the study site is influenced by the Brahmaputra-Jamuna river hydrology. The total drainage area of the Brahmaputra-Jamuna River is approximately 600,000 km^2, of which 47,000 km^2

lies within Bangladesh (Vij and Shenoy, 1968; Goswami, 1985; Thorne *et al.,* 1993). The Brahmaputra-Jamuna is characterised as low flows during the dry season in winter and high flows during the summer monsoon. The maximum discharge of the Brahmaputra-Jamuna at Bahadurabad is 100, 244 m^3s^{-1}, whereas minimum and average flows are 2,427 m^3s^{-1} (FAP 25, 1992). The bankfull discharge of the river varies from 45,000 m^3s^{-1} to 60,000 m^3s^{-1}, which corresponds to a range of about 0.75 metres in water level (BWBD, 2006).

Figure 3.10 shows the flood frequency variations (water level) of the Brahmaputra-Jamuna River in Bangladesh for the 2008, 2007, 1998 and 1988 floods. Respondents reported that the floods of 1988, 1998 and 2007 were very large while 2008 was a normal flood. The 1988 flood was the most severe. In the early monsoon, the trend of increasing water levels was similar for all years but variation were obsersed among the peak durations. The trend of water level recession varies in different years.

This large River influences on the floodplain hydrology both banks (west and east) of the main tributaries of the Brahmaputra-Jamuna are the Teesta and Karatoya-Hurasagar (both on the west bank), while the distributaries are the Old Brahmaputra, Dhaleswari and Gaugeghata (*Gheor*), all on the east bank. Locally, the Gaugeghata (*Gheor*) river flows perennially through the study site. Therefore, in terms of micro scale hydrological characteristics, the Gaugeghata river hydrology influences the study site. Another distributary, the Old Dhaleswari, affects the eastern edge of the study site during monsoon season. The annual hydrograph of the local Gaugeghata River shows high seasonal fluctuations in water stage (Figure 3.11).

The water level hydrograph shows a comparison between two different flood events; abnormal flood (*Bonna*)in 2007 and normal flood (*Barsha*) in 2008. It is evident from the hydrograph that water level reached into two sharp peaks (6 August and 17 September) in 2007, which exceeded the risk level, while in 2008, only the 6 August peak reached the risk level and over the rest of the monsoon period it ranged from normal to moderate flows.

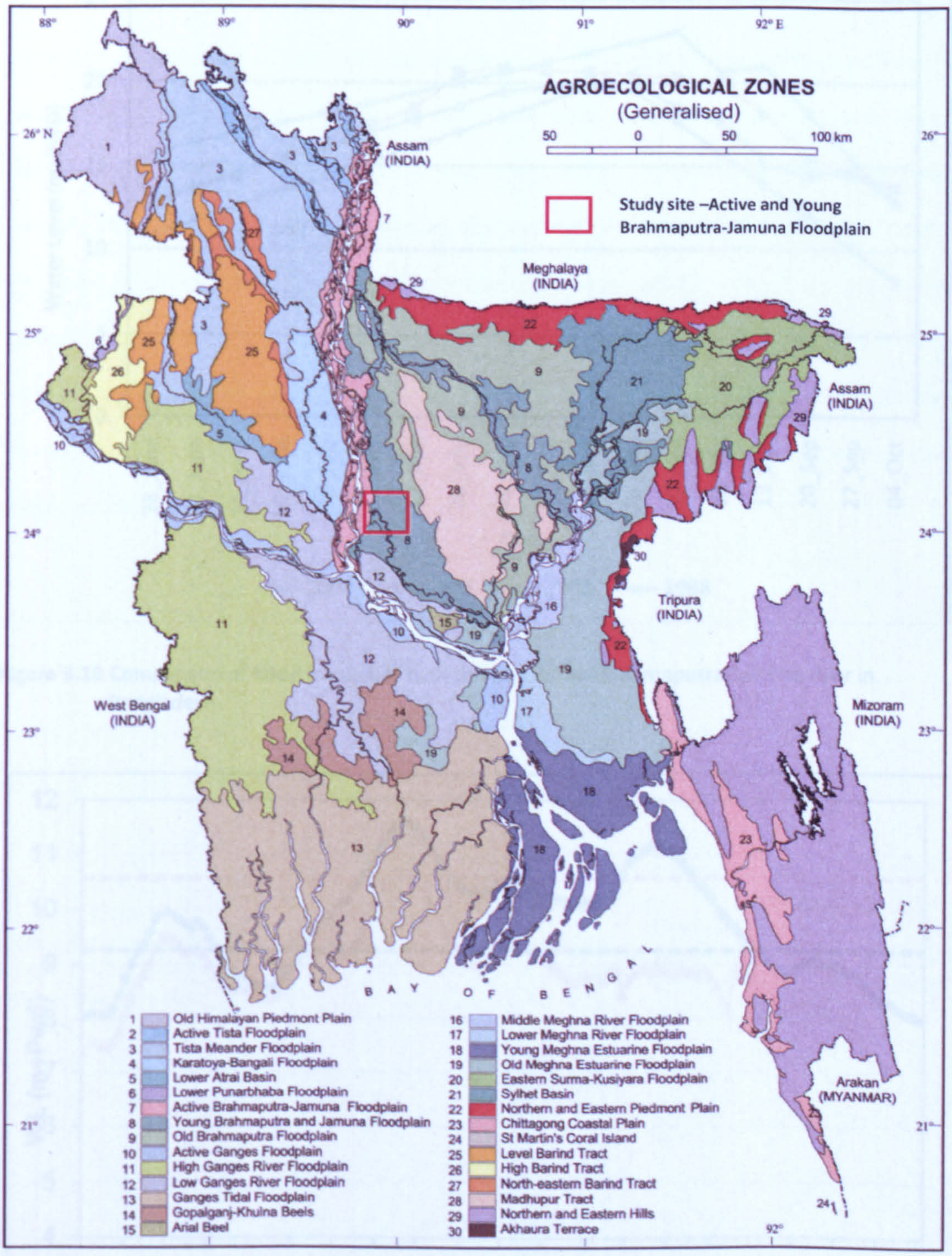


Figure 3.9 Location of the study site in the Agro-ecological zones of Bangladesh (Source: modified after SRDI, 1990)

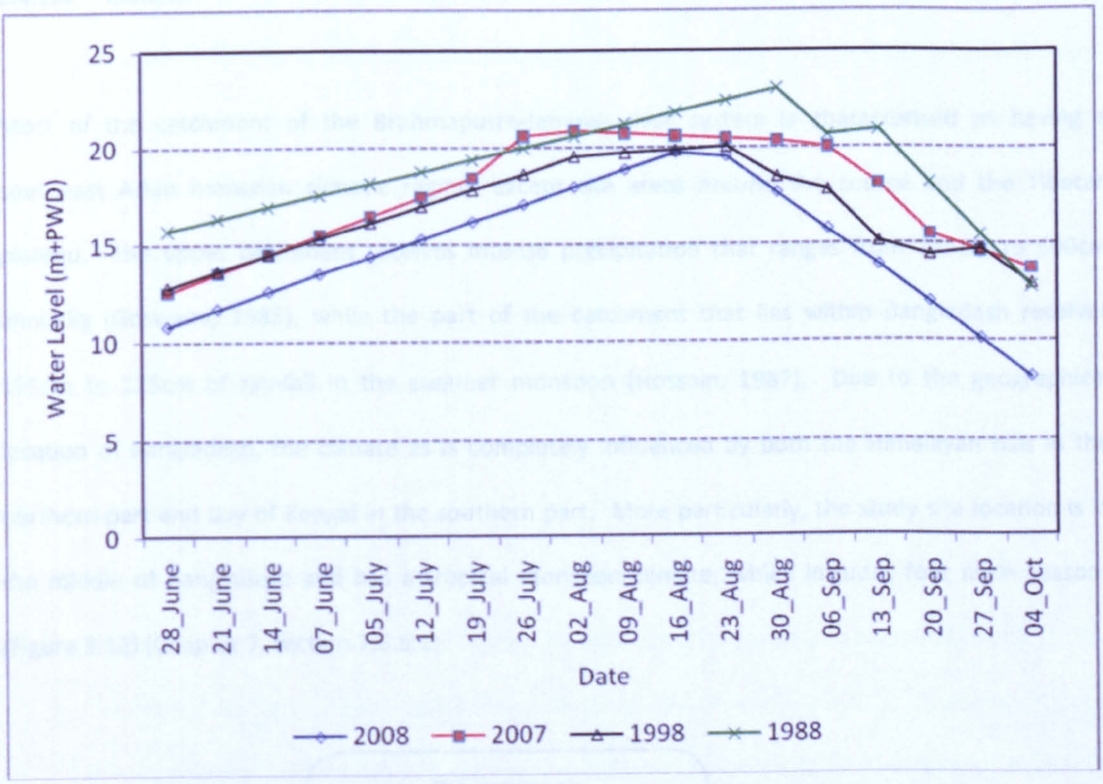


Figure 3.10 Comparison of flood frequency hydrographs for the Brahmaputra-Jamuna river in Bangladesh

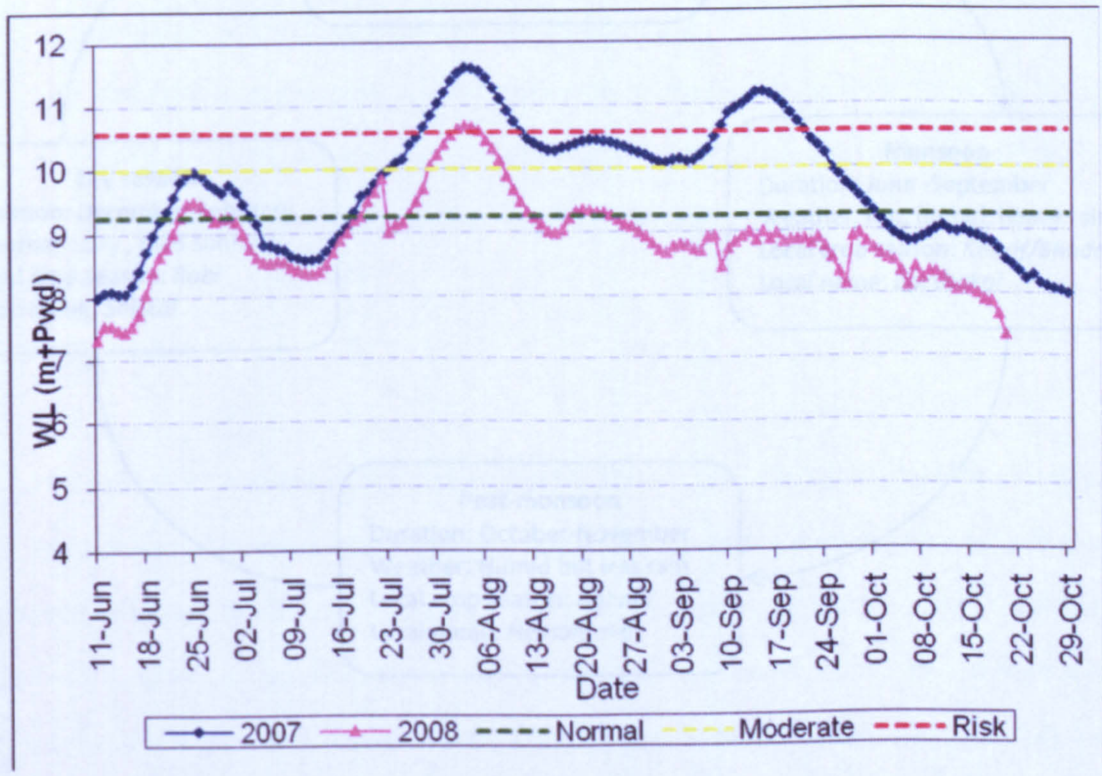


Figure 3.11 Water level hydrograph for the Gaugeghata River at *Boro Bania* village in Daulatpur Upazila, Manikganj District in Bangladesh of 2007 and 2008

3.4.2.4 Climate

Most of the catchment of the Brahmaputra-Jamuna river system is characterised as having a southeast Asian monsoon climatic regime except the areas around the source and the Tibetan plateau. The upper catchment receives intense precipitation that ranges from 225cm to 500cm annually (Goswami, 1985), while the part of the catchment that lies within Bangladesh receives 175cm to 225cm of rainfall in the summer monsoon (Hossain, 1987). Due to the geographical location of Bangladesh, the climate as is completely influenced by both the Himalayan hills in the northern part and Bay of Bengal in the southern part. More particularly, the study site location is in the middle of Bangladesh and has a tropical monsoon climate, which includes four main seasons (Figure 3.12) (Chapter 7, section 7.6.5.1).

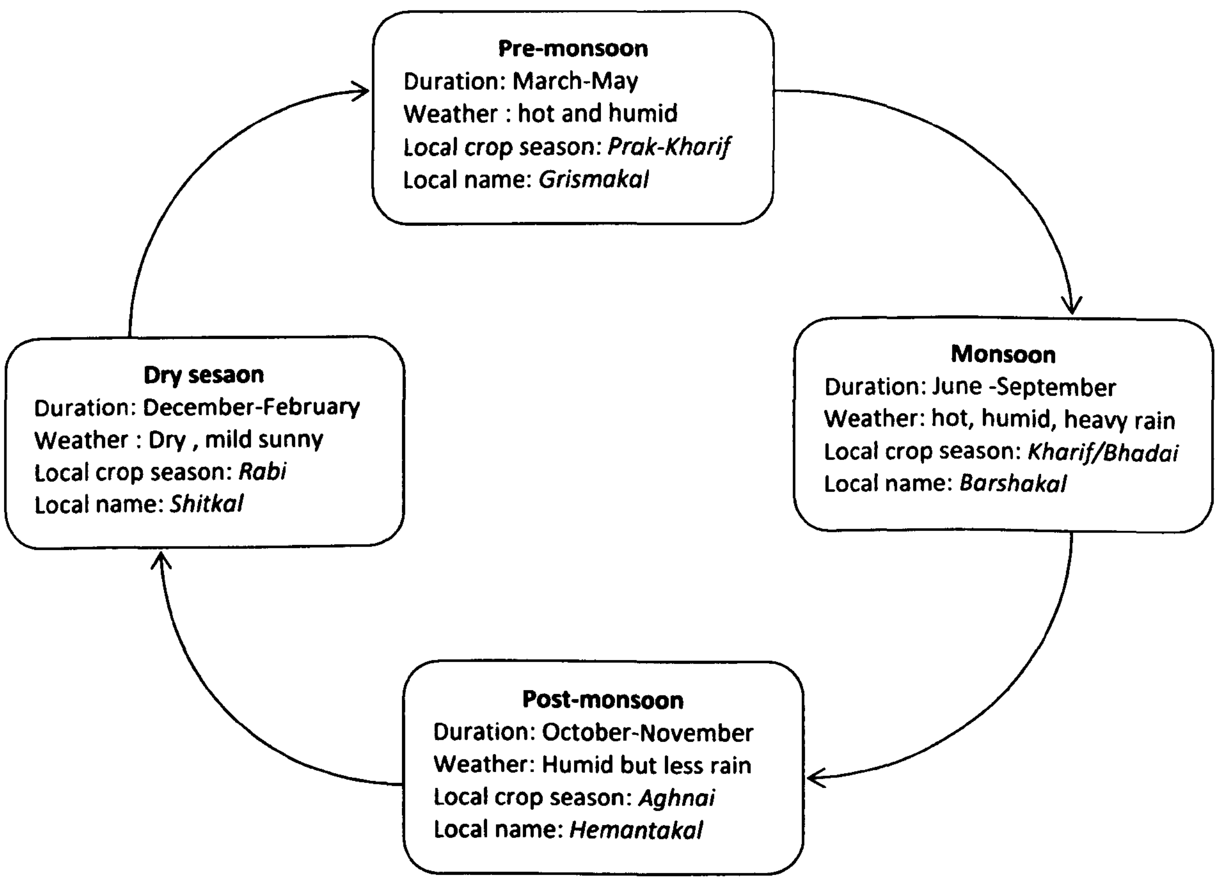


Figure 3.12 Schematic diagrams of the climatic seasons of study area.

- The pre-monsoon (*Prak-Kharif- summer*: March–May) has a maximum temperature of around 35^{0}C and a minimum temperature of around 20^{0}C. Tropical cyclones and heavy north-westerly thunderstorms with strong winds occur, and the month of April is usually the hottest. The average rainfall is 48.7 cm and the wind direction is mainly south-west. Evaporation ranges from 95 to 165mm.
- The monsoon (*Kharif/ Bhadai*-rainy seasons: June-September) temperatures range from 24 to 33^{0}C with an average rainfall of 130.8cm, which constitutes ~90% of the total annual rainfall. The wind direction is mainly southeast and evaporation rates range from 100 to 125mm.
- The post-monsoon (*Prak Rabi/ Aghnai/ Haimantic*- early winter: October-November) is known as the 'mild cold-dry season' and experiences a temperature range of 12 to 25^{0}C. The month of January is considered the coldest month of the year (10^{0}C). Sometimes, local thunderstorms and depressions that occur in the northern part of Bangladesh and as a result the study site receives an average rainfall of 5.6 cm from such storms (which is less than the evaporation total of 500 to 750mm). During the winter, the wind is mainly from a north-easterly direction (SRDI, 1990 and BMD, 2008).
- The dry season (*Rabi/ Shitkal- Winter* December-February) is known as the *rabi* season in Bangladesh. The season is characterized as dry, mild and sunny season experiences a temperature range of 10-18^{0}C. The average precipitation is < 4cm.

3.4.2.5 Soils

Spatial and temporal variations in the physiographic, climatic and hydrological characteristics of the whole Brahmaputra-Jamuna River basin are reflected in the soils of the downstream Brahmaputra-Jamuna floodplain. This is the case because the processes responsible for formation and development of the floodplain soils are interrelated with the fluvial characteristics of the upper Brahmaputra-Jamuna River. According to Goswami (1985), the upper catchment soils mainly consist of sands with an admixture of cobbles and boulders, which are underlain by tertiary sandstone. However, the soils of the Brahmaputra-Jamuna floodplain are composed of a grey-brown, fine to medium-grained alluvium formed of sand, silt and clayey particles with relatively un-weathered fluvial and aeolian deposits. Brammer (1995) classified the Brahmaputra-Jamuna floodplain as having non-calcareous grey floodplain soils, non-calcareous alluvium, non-calcareous dark grey floodplain soils, shallow and deep grey terrace soils, deep red brown terrace soils and calcareous dark grey floodplain soils . These soils have mainly developed through lateral channel migration and vertical accretion (Coleman, 1969). The study site lies within the active and young floodplain and displays characteristics generated by adjacent Jamuna fluvial system and soil type is non-calcareous grey floodplain soil. Considering the physical properties, the soils are mainly silt and sand dominant in the medium high land and medium lowland areas of the active and young floodplains. The physical and chemical properties of soil of the study site are derived from the Soil Resources Development Institute (SRDI, 1990). This institution reports upazila wise soil suitability index for agricultural development. According to the SRDI report, the p^H ranges from 5.4 to 5.5 for sand and 7.0 to 7.2 for silt, with organic matter making up 0.12-0.16% of the soil by mass. The average chemical characteristics of the sand component of the soil are: Ca, Mg, K, 4.6, 1.1, and 0.58 meq/100ml, respectively with N, P, S, B, Cu, Fe, Mn, and Zn present at levels of 27, 43, 62, 0.68, 2.7, 142, 20, and 3.2 Ag/ml, respectively). The silt-dominant soil is characterised as Ca, Mg, K (6.0, 0.87, 0.55 meq/100ml, respectively) and N, P, S, B, Cu, Fe, Mn, Zn (24, 60, 99, 1.3, 3.3, 80, 25, 2.6 Ag/ml, respectively). These values are indicative of the level of soil suitability for crop production.

3.4.2.6 Vegetation

Due to its high climatic and physiographic variability, the Brahmaputra-Jamuna catchment features natural vegetation that ranges from sub-tropical evergreen and mixed deciduous forest to meadows. Most of the vegetation of the Brahmaputra-Jamuna floodplain is subjected to inundation by monsoon flooding more or less every year and the siltation is supporting a rich diversity of vegetation species. As the study site is located adjacent to the Jamuna River, within the active and young Jamuna river floodplain, the nature of the soil plays a vital role in conditioning the site's ability to support different species of vegetation. The medium to high land is mainly covered with tree species that include mango (*Mangifera indica*, Anacard), jackfruit (*Arocarpus heterophyllus*, Moraceae), palm (*Borassus* *flabellifer*, Palmae), Mehagani (*Swietenia macrophylla*, Meliaceae), Koroi (*Albizia procera*, Leguminosae) *and* bamboo bushes (*Bambusa balcooa*, Graminae).

The medium/low land areas are covered with *Hizal (Barringtonia acutangula*, Myrtaceae) Bonjiga (*Trema orientalis*, Ulma) *and Zika* (*Lannea coromandelica*, Anacardiaceae). Near the channel, the shrubs including sun grasses, catkins and *kaisha* (*Imparata cylindrical)* are dominant, together with some tree species. Seasonal variations occur, but more generally for the shrubs than for the tree species. Moreover, the floodplain is intensively cultivated and crops widely grown in this area include rice paddy, jute, sugarcane, wheat, peanuts, various types of pulses and sesame.

3.4.3 Anthropogenic setting

The people who inhabit the land adjacent to the Brahmaputra-Jamuna River are experienced in floodplain living and possess a well-adapted attitude to the behaviour of the river. Due to the prevalence of riverbank erosion, the area is under developed in terms of education, communications, and economy. Over 95% of people who live in this floodplain are engaged in subsistence agriculture. In terms of economic condition, the people are mainly poor and perpetually struggle to meet their basic needs. Therefore, they have to rely on the optimum use of the land to maximise its production capability.

3.4.3.1 Land use

The monsoon climate, land type and behaviour of the Brahmaputra-Jamuna river dominate the land use pattern. Seasonal inundation, driven by heavy monsoon rain and river flooding, provide the moisture and sediment that define the land's suitability for crop production. The active and young Jamuna floodplain is predominantly cultivated for subsistence farming. About 80% of the available land is used for cultivation with the remaining 20% used for settlements, *hat-bazar* (markets), public buildings and communications infrastructure. Settlements and infrastructures are mainly located in areas that are, in most years, flood-free. During the pre-monsoon (March-May) season, land is used mainly for *IRRI* (one kind of paddy invented by International Rice Research Institute) paddy, *boro* (dry season paddy) paddy, and sugarcane. During the monsoon (June-October) season, land is used for *aman* and *aus* paddy, sesame and Jute. In the post-monsoon (November-February) season it is used to grow millets, peanuts, oilseeds and vegetables. Catkin grass and sun grass (*Kiasha*) appear naturally in the sand dominant areas. According to the district (*Zila*) 'Series *of Manikganj'* (2001), the net temporary cropped area of the study site (*Bara Bania)* is 276 hectares, while the gross cropped area is 500 hectares. Most of the land is used to grow two or more crops each year, with a cropping intensity of more than 200% (ISPAN, 1995). Recently, a general trend has appeared that in the dry season some medium to high land is also being using for irrigated crops, in particular for IRRI paddy. The farmers use more fertilizer for irrigated crops than for rain-fed crops. They mainly use urea, TSP and MP fertilizer at higher than the recommendation rates to produce better yields from the agricultural fields. Tables 3.4 and 3.5 show the cropping pattern used in the area and the land use characteristics of the study site (*Bara Bania*).

Table 3.4 Area under crops in different seasons

Crops	**Area in hectares**
HYV Boro paddy	47
Local paddy	253
Wheat	15
Potato	2
Vegetables	1
Spices	2
Pulses	76
Oil seeds	90
Sugarcane	1
Jute	13

Source: BBS, 2007

Table 3.5 General land use type of the study site

Land use types	**Area in hectares**
Homestead area	22
Owned area	356
Operated area	344
Cultivated area	276
Net Irrigated area	68
Net fertilized area	223

Source: BBS, 2007

3.4.3.2 Demography

According to the District(*Zila*) population census, the study site(*Bara Bania* village) has a population of 2,515, of which 1,286 are male and 1,229 are female(BBS, 2006). The study site has an annual growth rate of 1.03%. Figure 3.13 shows the dynamics of the population growth rate of the study site. In 1951, the population growth rate was 2.2% and it was 3.3% in 1961. After independence, the first population census undertaken in 1974 showed the growth rate to be 1.62%. Government initiatives and public awareness and education have together resulted in the declining trend in population growth. The age and sex ratio is 100:96. Figure 3.14 and Table 3.6 show that 51% of people are dependent and only 49% are working. Among the dependent population, the male to female ratio is almost equal and, although the working percentage of people is male-dominant, the female percentage is mainly engaged in household and family-centred tasks. As a result, a large proportion of the population are not actually engaged directly in agriculture. In addition, a total of 31% of the population is below 10 years of age. Of the over 10 year olds, 23.8% are dependent, 1.3% are looking for work, 36.5% are engaged in household work and remaining 38.4% percent are working. The population density is 660 per square kilometre and the average land area per capita is 0.15 hectare (BBS, 2006).

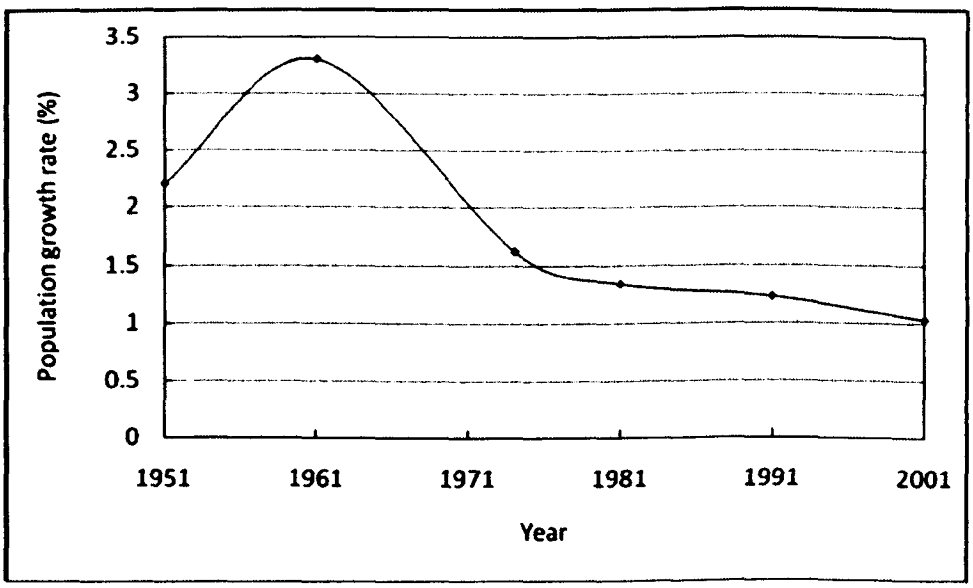


Figure 3.13 Trend of population growth rate in *Bara Bania* village

Table 3.6 Population by age group and sex in study site (*Bara Bania* village)

Age group (Years) Sex	0-4	5-9	10-14	15-17	18-34	35-59	60 +
Male	194	213	170	80	248	290	91
Female	202	165	147	36	373	214	92
Total	396	378	317	116	621	504	183
%	0.16	0.15	0.13	0.05	0.25	0.20	0.07

Source: BBS, 2007

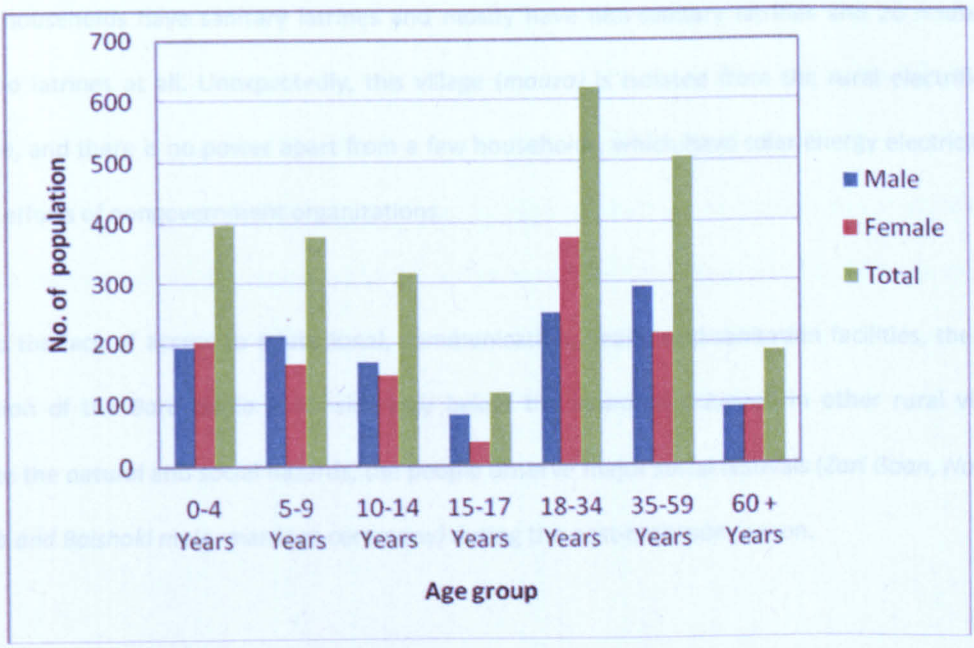


Figure 3.14 Population distributions by age group and sex of the study site

3.4.3.3 Sociology

The study site represents the actual rural characteristics of Bangladesh. There are 547 households in the *Bara Bania mauza*, of which 465 are Muslim (2,132 people). Only 82 households belong to the Hindu religion (383 people). The average size of a household is 4.6 people. Table 3.7 provides the marital status of people in the study site. The literacy rate is 23 percent, of which 17 percent are male and 6 percent are female. Although rural families are generally characterised as paternal, women also play a vital role, performing household and post-harvest work that is largely unacknowledged.

For women and children, healthcare remains poor due to a lack of governmental health facilities and, as a result, women and children's health is more vulnerable than men's health.

The housing condition is mostly *Kancha*, which is made of locally available sun grass, timber and bamboo; and villagers those are economically a bit solvent they have the semi-*paka* made of corrugated iron sheet (*tin* sheet). Most households drink tube-well water, and a few of them use pond and river water. There are virtually no sanitation and drainage facilities in the study area. Only 10-15 households have sanitary latrines and mostly have non-sanitary latrines and 20 households have no latrines at all. Unexpectedly, this village (*mauza)* is isolated from the rural electrification scheme, and there is no power apart from a few households, which have solar energy electricity due to the efforts of nongovernment organizations.

Due to the lack of access to educational, communication, health and sanitation facilities, the social condition of the *Bara Bania* is considerably below the standard achieved in other rural villages. Despite the natural and social hazards, the people observe major social festivals (*Zari Gaan, Nabanna uthsab and Baishaki mela,* marriage ceremony*)* during the post-monsoon season.

Table 3.7 Marital status of people populating the study site

Sex	Marital status			
	Never married	**Married**	**Widow**	**Divorced**
Male	341	532	6	0
Female	212	558	1	91
%	32	63	0.4	4.6

Source: BBS, 2007

3.4.3.4 Economy

The main sources of income for people in the study area are agriculture, forestry and livestock (57%), fisheries (12%), agricultural labour (14%), non-agricultural labour (2%), handlooms (0.4%), business (7%), transport (1%), services (4%) and other (3%) (BBS, 2007). Flood hazards affect the study site's economy. For example, the catastrophic flood of 2007 acted as the main natural hazard in the study area, although this type of mega-flood also triggers periods of higher than normal agricultural production in the following post-monsoon season. The floodplains are of immense economic significance to the area due to its dependence on the seasonal flows of floodwater and sediment (Welcomme, 1979; Junk *et al.*, 1989; Dudgeon *et al.*, 1994).

As the rural economy is dominated by agriculture hence, a better policy is needed for sustainable management of the floodplain in order to improve the agricultural sector of the economy. However, it must not be forgotten that non-farming activities are also important to development of the rural economy. Significant, non-farming activities centre on human labour and development services. In these contexts, non-governmental organizations (NGOs) are working to develop the rural livelihood through micro-credit programmes due to the lack of governmental initiatives. Rural people generally take loans from NGOs for agricultural work, to buy seeds and fertilizer and so that rural women can contribute substantially to economic development through development of livestock, poultry, small homestead gardening for vegetables, and the development of small, handloom based cottage industries.

Seasonal unemployment is another problem in the study site, and is a more general scenario all over the flood prone area in Bangladesh. Early in the monsoon, labourers are kept busy harvesting local varieties of paddy (*aus* and *boro* paddy) and jute, but they become unemployed for 2-3 months during the monsoon season because most of the land is flooded. At these times, land-less farmers and labourers migrate to the town to look for non-formal work. In the study area, 336 households remain engaged in farming throughout the year, while 211 households turn to non-farming activities. Farm sizes range from small (< 1 ha), medium (1-2 ha) to large (> 2 ha), of which 70 % of households are classified as small farms, 25% are classified as medium farms and only 5% as large farms (Figure 3.15).

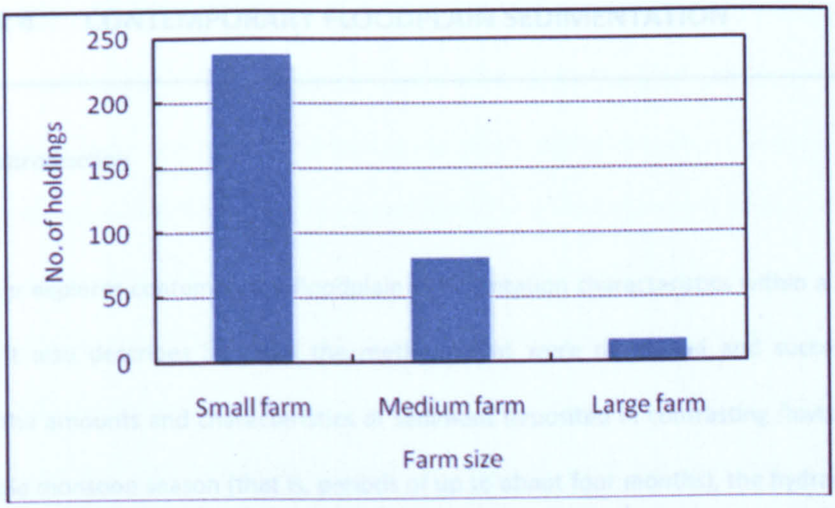


Figure 3.15 Number of households engaged in agriculture by farm size.

The rural economy remains completely different to the urban economy as it relies overwhelmingly on subsistence agriculture. Hence, the government is engaging in bottom-up planning for agricultural development with the aim of better land use management to improve poor rural livelihoods. In this context, optimum use of the floodplain to maximise crops yields while using natural resources sustainably is central to developing the rural economy and it follows that the key to delivering improvements to rural economies lies in improved land use decision making.

CHAPTER 4 CONTEMPORARY FLOODPLAIN SEDIMENTATION

4.1 Introduction

This chapter explores contemporary floodplain sedimentation characteristics within a spatiotemporal context. It also describes in detail the methods that were developed and successfully used to measure: the amounts and characteristics of sediment deposited in contrasting fluvial environments over a single monsoon season (that is, periods of up to about four months), the hydraulic parameters driving sedimentation, and the analytical techniques used to process the field data and investigate the relationships between the hydraulic parameters of the flood (water depth, flood duration and flow velocity) and sediment deposition. Finally, it presents a synthesis of the results of the floodplain sedimentation study that highlights the influences of flood hydrology and floodplain morphology on floodplain sedimentation at different spatial and temporal scales.

4.2 Terminology

A range of terms are used to describe the addition of flood sediments to the floodplain, including 'sediment deposition', 'sediment accumulation' 'sediment accretion' and, most simply, 'sedimentation'. These terms are used more or less frequently in different disciplines (geology, geomorphology, sedimentology, biology and engineering) and in the contexts of multiple physical, chemical and biological processes (Thomas and Ridd, 2004). These terms imply no timescale and so it is necessary to define the period with which a particular study is concerned. In this context, many studies refer to the 'short-term time scale'. This phrase is quite ambiguous and has been used by various researchers to define 'contemporary', 'modern' or 'recent' time scales. For example, researchers have taken a 'short term time scale' to be less than 1 month (Pasternack and Brush, 2001), less than 1 year (Knaus and Van Gent, 1989; Childers *et al.*, 1993; Parkinson, *et al.*, 1994; Wijnen and Bakker, 2001), less than 10 years (Cahoon and Lynch, 1997), or less than 100 years (Nittrouer *et al.*, 1979 and Lynch *et al.*, 1989). Courp and Monaco (1990) considered a time scale of less than 1 year to be 'contemporary', less than 100 years to mark a 'recent' or 'short' time scale, and less than 4000 years to refer to the early Holocene period. Conversely, Parkinson *et al.* (1994) catalogued a time scale of 1-100 years as 'historical' and hundreds to millions of years as being a 'geological' time scale. It is therefore important to clearly define the time scale over which sediment accumulation rates and processes are being considered in any particular the study.

According to McKee *et al.* (1983:631), "sediment deposition refers to the temporary emplacement of particles in 100 day temporal scales, while accumulation is the net sum of many episodes of sediment deposition, and removal in a 100 years scales". Strictly, the term 'sedimentation', refers to particles settling under gravity through the water column to the bottom of a water body (Thomas and Ridd, 2004). Larcombe and Woolfe (1999:163) describe 'vertical sediment accumulation' as the "processes of increasing in thickness of a sediment body caused by addition of materials at its upper surface" (Thomas and Ridd, 2004:96). On this basis, it represents the outcome of complex interactions between sediment particle fluxes (Lund-Hansen *et al.*, 1997), mineral sediment accumulation and the formation of peat (Ellison, 1993) which involves not only sediment deposition and erosion, but also plant production and decomposition (Cahoon *et al.*, 2000). Based on this brief review of terminology, I would define the present study as monitoring contemporary, sediment accumulation on the floodplain.

4.3 Data used in this study

Field site surveys of hydrological and morphological attributes are the main sources of information for this research. In addition, the research utilizes different types of data, including cadastral information obtained from cadastral (*mauza*) maps, topographic maps and transects surveys, water levels, flood durations, water velocities and suspended sediment data obtained by sampling during the flood and information on sediment accumulation and deposited sediment sizes obtained from measurements made before and after the flood. The sources and collection procedures for these data are each different and their accuracy varies widely due to natural variability, the limitations of measuring instruments and uncertainties concerning the procedures employed to collect, process and store the data.

4.4 Methods of data collection

4.4.1 Land form heights

A transect levelling survey was conducted performed to get the local topographical elevation of the study site. The dumpy level (using instruments readily available in Bangladesh) was used to perform detailed measurements. Four transects were surveyed, each extending from the natural levee to the back swamp. Transects were selected after field reconnaissance, where absent of any natural or man-made barriers. The reference datum for elevations was taken from benchmark points established by the local public works department and then checked with the topographic map produced by Survey of Bangladesh. The rise and fall calculations were performed by finding the difference between the first reading and the second reading to decide if the ground was rose or fell between the two points. Thus, the difference in height from point A to point B was determined in terms of either rise or fall and then recorded in the appropriate column of the field book. Once the rises and falls had been calculated, the new reduced levels at each point were found. The error was checked by calculation of difference between first and last reading, difference between sum of rise and sum of fall, and difference between first reduced level and last reduced level found all were equal and concluded that the entries and calculations were performed accurately and without significant error. At the time of the leveling survey, the latitude and longitudinal records of surveyed stations points were taken by using GPS. The leveling survey results then attributed as a point data and visualize the landforms heights differences by using the Arc view GIS.

4.4.2 Hydrologic data

The Bangladesh Water Development Board (BWDB) maintains gauging stations on major rivers, tributaries and distributaries throughout Bangladesh. The gauging stations at Bahadurabad, Sirajganj and Aricha along the Jamuna River (Figure 4.1) are part of this network. The selected study site is only 5km away from the nearest gauging station on the Jamuna River and so water level and velocity data collected there can be used to represent conditions in the main river.

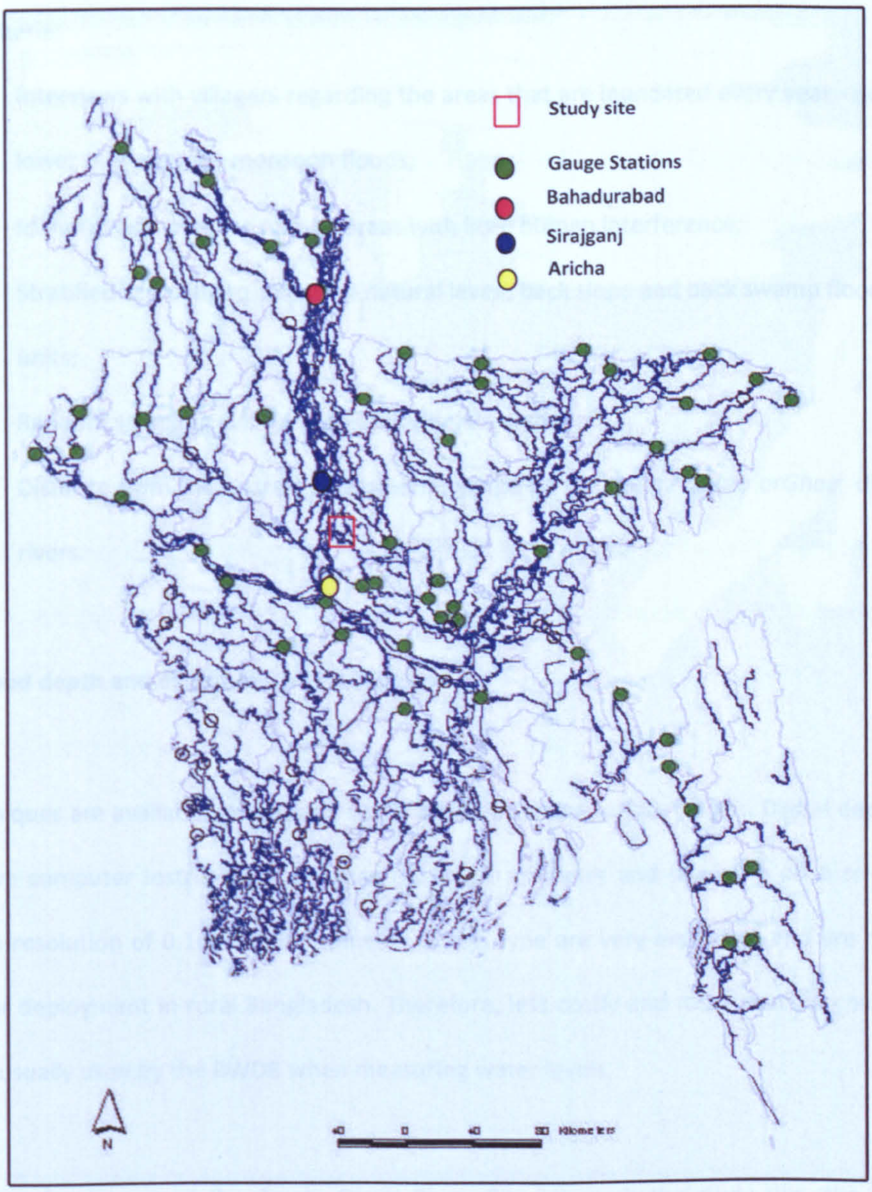


Figure 4.1 Available river gauge stations all over the Bangladesh and along the Brahmaputra- Jamuna River in Bangladesh (Source: FFWC, 2006)

However, data for the main channel cannot be used to represent conditions on the floodplain and so field surveys were undertaken during the floods to record the corresponding water depths and velocities at selected sampling sites in the study area. Sample sites were selected based on the following criteria:

- Interviews with villagers regarding the areas that are inundated every year - even during lower than average monsoon floods;
- Identification of more natural areas with little human interference;
- Stratified sampling to cover the natural levee, back slope and back swamp floodplain units;
- Random sampling within each of floodplain unit; and
- Distance from the nearest hydrometric gauge on the *Gauge Ghata* or*Ghoir* distributary rivers.

4.4.2.1 Flood depth and extent of flood inundation

Many techniques are available to measure water depth or water surface height. Digital depth gauges and the dive computer instruments measure the depth of water and display it on a screen, most usually to a resolution of 0.1m, but instruments of this type are very expensive and are not readily available for deployment in rural Bangladesh. Therefore, less costly and more easily accessible staff-gauges are usually used by the BWDB when measuring water levels.

A distributary, locally named the *Gauge Ghata* River, flows through the study site. The Centre for Environmental and Geographic Services (CEGIS) gathered monsoon season (June to October) water level data at a site on the *Gauge Ghata* River between 2004 and 2007 as a part of the Environmental Monitoring and Information Network (EMIN) project. In this study, these data were made available by CEGIS as a secondary source. In addition, during the summer monsoons of 2007 and 2008, flood depth data were also collected at four of the sediment sampling sites along the surveyed transects within the study area. At the beginning of the field study (and prior to monsoon inundation), a wooden gauging staff was set up (Photograph 4.1) at each of the sites and a local person was paid to take responsibility for measuring the water depth five times a day (at regular intervals between 6:00 to 18:00 hrs). The CEGIS water depth data was used only in checking the field hydrological data of 2007 and 2008. A point on the site was nominated as the depth reference or temporary benchmark (TBM) for the calculation of all water level measurements. During the field survey, several limitations became apparent. These include the influence of wind waves, waves from boats passing near the gauges and disturbance by people using the staff to tether their boats, which may introduce errors in observed water depth and levels. Attempts were made to limit these errors by weekly checking of the gauge level datum for each gauge against that for a nearby BWDB gauge.

4.4.2.2 Water velocities

Several types of current meter (anemometer, impeller, electromagnetic, Doppler, and optical strobe) are available for measuring water velocity at a point. Among these, simple anemometer and propeller type current meters are most commonly used for measuring overbank flow velocities in Bangladesh due to their easy accessibility and user friendliness.

Photograph 4.1 Staff gauge used to measure water level

Therefore, the present study used Geopack one-dimensional, Impeller-type flow meters (Model-MFP126). The instrument was deployed from a country boat, the position of which was fixed using a hand-held GPS. The direction of flow at the water surface was determined at each measuring point by tracking a floating bottle using a sextant. It is evident from theory that a reliable average velocity can be recorded at 0.6 of the total depth of the water below the surface for shallow flows, and from the average of readings at 0.2 and 0.8 of the depth for deeper flows. When taking a velocity reading, the wading rod was put on the bed and the water surface level marked with finger and thumb. Then, it was removed from the water, keeping the water surface mark and placing a rubber band 0.4 of the depth above the base. The impeller was then positioned next to the rubber band (Figure 4.2). In this way, at each vertical the velocity was measured at the same sediment sampling point. When the water was deeper than about 1 m, additional measurements were made 0.2 and 0.8 of the depth to calculate the average velocity and check this with the value obtained at 0.6 of the depth. The average flow velocity was calculated according to the Straub method, as recommended by the World Meteorological Organization (WMO, 2006). The measuring time in each point was 100 seconds at each depth. Additionally, surface flow velocities were measured by tracking surface floats and the results compared the values recorded using the current meters. Velocity data were collected on a weekly and fortnightly basis for the entire duration of monsoon floods of 2007 and 2008 at 25 locations distributed over the study sites and coinciding with the sediment sampling sites.

Several types of error were associated with the velocity measurements. Errors stem from the simple instrument used, the time allowed for the measurement of each point variability in the number of points in the vertical and the number of verticals used at a sampling station. These limitations could be reduced by using more sophisticated current meters and sampling techniques. However, the simple instrument and technique used in this study was appropriate because the local people engaged in data collection could gather and record the field data reliably with little training using this easily available and robust tool and sampling technique. It should be mentioned here that the BWDB use Ott current meters to measure flow velocity at their permanent stations, which is itself a one-directional device.

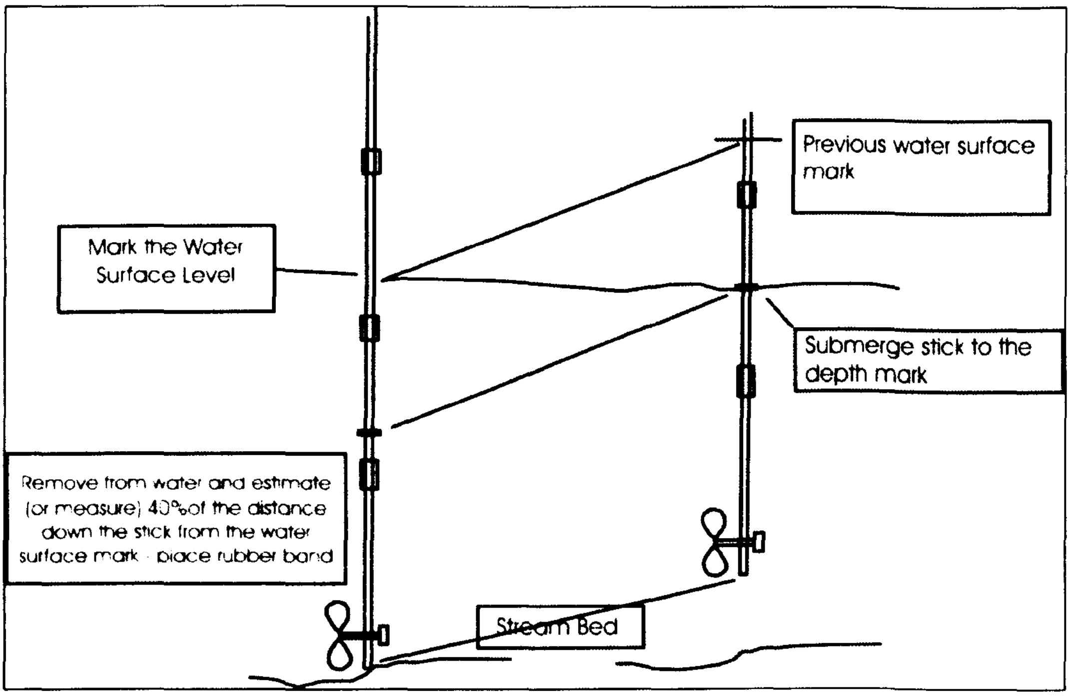


Figure 4.2 Velocity measurements at 0.6 of the depth

4.4.2.3 Flood inundation duration

A local person was engaged to record the dates on which inundation began, peaked and ended at the sampling sites during the summer monsoons of 2007 and 2008. These records were cross-checked with data from the nearest BWDB gauging station and records from the Flood Forecasting and Warning Centre (FFWC). Additionally, inundation depths were recorded at the same sites on a weekly basis. In 2007, inundation in the study area started on 11 June and it persisted, until the end of October. There was a severe flood in 2007, featuring major peaks in August and September that reached elevations close to those observed during the great floods of 1988 and 1998. In 2007, standing crops, property and infrastructure were damaged and daily life was severely disrupted for many households. People living in low-lying areas had to evacuate themselves and move their livestock and possessions to safe places. In contrast, the 2008 flood was about average in extent and duration. Inundation in the study area started on 28 July, peaked on 25 August, and ended by 25 September.

4.4.2.4 Suspended sediment concentration

The concentration and calibre of suspended sediment carried by the floodwater is an important parameter in the floodplain sediment budget. Consequently, a variety of techniques have been developed to measure suspended sediment. For example, automatic pump samplers *(calibrated using USGS DH-48 depth-integrated samplers)* (Wren *et al.*, 2000) and turbidity sensors (Gippel, 1989 and 1995 . Comparing the two, the turbidity sensor is appropriate for long-term monitoring, particularly if the study site is not easily accessed and flood events occur irregularly. The approach suggested by Brasington and Richards (2000) based on physically collecting sample of floodwater in bottles was selected to sample suspended sediment concentration in this study. The main considerations leading to this decision were the high cost and non-availability in Bangladesh of automated or continuous samplers, coupled with the free availability of simple equipment, easy site access and low cost of fieldwork.

During the 2007 monsoon, 40 x 500ml water samples were collected from just below the water surface at inundated sites distributed across the study area to determine the suspended sediment concentration (Figure 4.3 and Table 4.1). The first batch of samples was collected on 25 July 2007 when flooding began. Two further batches of samples collected during the flood peaks on 6 August and 17 September 2007, respectively. The last batch of samples was collected on 2 October 2007, when the flood was receding. The same procedures were deployed during the 2008 monsoon flood, with the equivalent samples being collected on 28 July, 25 August and 7 September.

Two techniques are widely used to measure the suspended solids in fluvial flows; filtering and evaporation. Filtering retains the suspended particles but passes dissolved material, so that the resulting data represents the suspended sediment concentration. Evaporation captures both dissolved and suspended material and so the results represent the concentration of total suspended solids. The use of the evaporation technique in this study therefore overestimates suspended sediment concentrations because it includes dissolved material. The concentration of dissolved material in rivers like the Brahmaputra is customarily around 100 mg/l. Hence, the use of evaporation rather than filtering in this study is likely to have resulted in systematic overestimates averaging in the order of 5% in the reported suspended sediment concentrations.

It is also important to mention here that over 90% of the suspended sediment carried by overbank flows is customarily composed of wash load, with less than 10% of the sediment being as coarse as that found in the river bed. Wash load is quite evenly distributed through the water column, while the concentration of coarse load increases with depth beneath the surface. In this study, lack of access to the sophisticated equipment needed to sample at depth meant that suspended sediment samples had to be collected from just below the water surface, where the concentration of coarse material is relatively low. This would result in systematic underestimation of the suspended load by something less than 10%, due the coarse load being under-sampled. It may, therefore, be concluded that any errors in calculated suspended sediment concentrations stemming from those the use of evaporation rather than filtering to separate the solids from the water collected in field sampling are likely to have been offset by those due to under-sampling of coarse sediment.

It may be concluded that the suspended sediment concentration reported in this thesis best represent the concentrations of total suspended solids. This is appropriate given that it is the finer (wash load) particulate sediments and dissolved materials that are most important to floodplain agriculture. In this context, the use of the evaporation technique was appropriate.

Table 4.1 Identification codes for suspended sediment samples

Sampling Locations	**Identification Codes**	
	2007	**2008**
Natural levee	SS01_07, SS02_07, SS05_07, SS09_07, SS21_07, SS23_07, SS25_07, SS26_07, SS27_07	SS01_08, SS02_08, SS05_08, SS09_08, SS21_08, SS23_08, SS25_08, SS26_08, SS27_08
Back slope	SS03_07, SS04_07, SS06_07, SS07_07, SS10_07, SS11_07, SS12_07 SS15_07, SS16_07, SS17_07, SS22_07, SS24_07, SS28_07, SS30_07, SS33_07, SS34_07, SS35_07, SS38_07, SS39_07, SS40_07	SS03_08, SS04_08, SS06_08, SS07_08, SS10_07, SS11_08, SS12_08, SS15_08, SS16_08, S17_08, SS22_08, SS24_08, SS28_08, SS30_08, SS33_08, SS34_08, SS35_08, SS38_08, SS39_08, SS40_08
Back swamp(*Beels*)	SS18_07, SS19_07, SS20_07, SS29_07, SS31_07, SS32_07	SS18_08, SS19_08, SS20_08, SS29_08, SS31_08, SS32_08
Khal (Seasonal water flow)	SS08_07, SS13_07, SS14_07, SS36_07, SS37_07	SS08_08, SS13_08, SS14_08, SS36_08, SS37_08

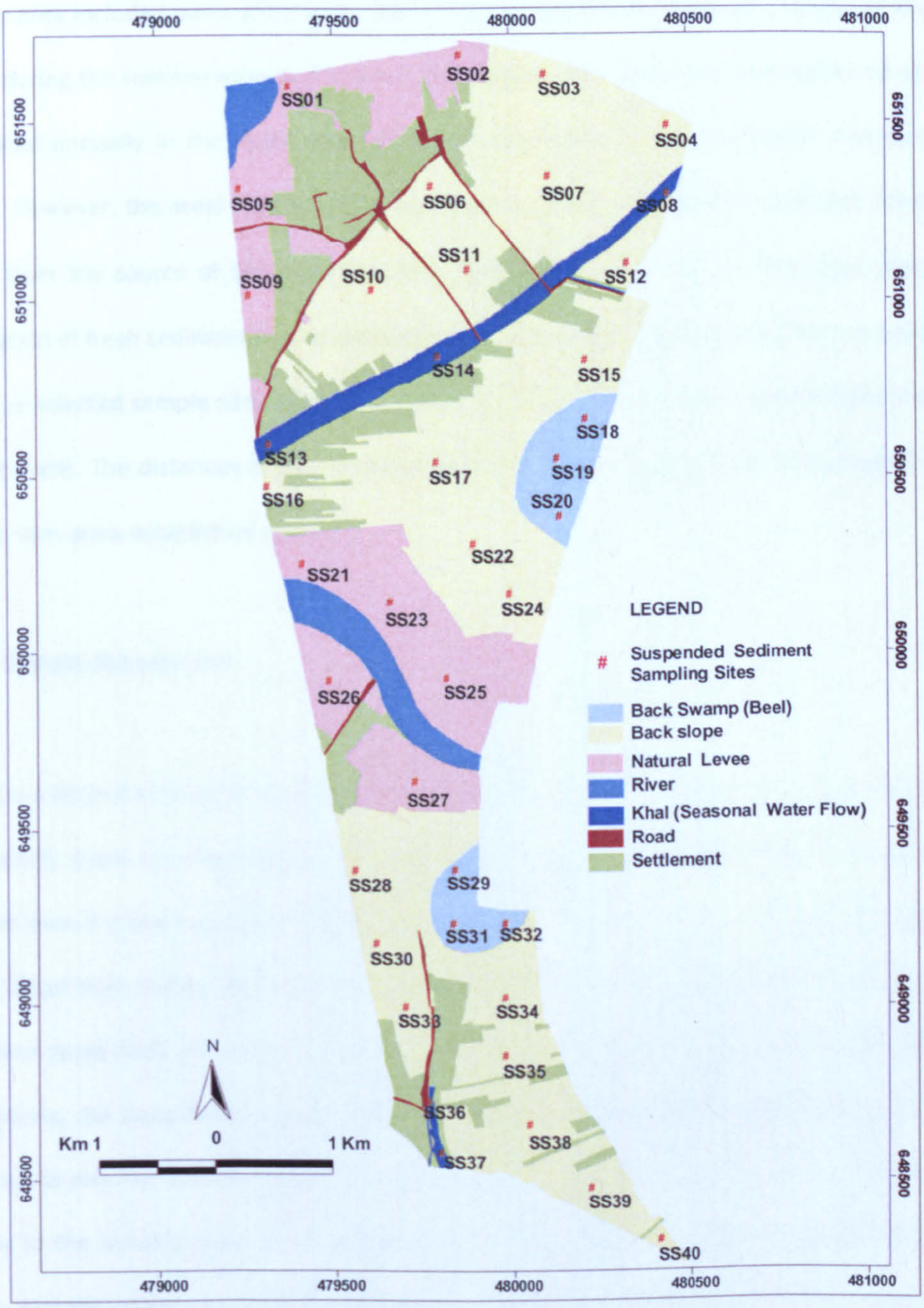


Figure 4.3 Suspended sediment-sampling locations

4.4.3 Floodplain sediment accumulation data

The study area included parts of both the active and young Jamuna floodplain, which are inundated annually during the summer monsoon season. The thickness and grain-size composition of sediments accumulated annually in the study area are mainly dependent on the magnitude and duration of flooding. However, the areal distribution of sediment thickness and particle size is also a function of distance from the source of the sediment-laden floodwater – the river. In this study, the vertical accumulation of fresh sediment on the floodplain was monitored in 2007 and 2008 using marker beds installed at selected sample sites prior to the onset of flooding that were excavated after the end of the flood event. The distances of the sampling sites from the river were measured carefully by tape when the sites were established in 2007.

4.4.3.1 Sample site selection

Flooding is a natural phenomenon that may occur with low or high magnitude in any particular year. Consequently, it was essential to position the sample sites in locations that would almost certainly be inundated even if a low magnitude flood should occur, but which would still be accessible should the flood be larger than normal. For this reason, exploratory visits were made during May 2007 to select appropriate study sites at which to monitor sediment accumulation. Based on these exploratory investigations, the *Bara Bania mauza* of *Daulatpur Upazila* in *Manikgonj* district was selected as a study area to monitor sedimentation. The factors considered in the selection of study sites were; proximity to the Jamuna River; its flood regime; the physiographic and relief characteristics; human activities and disturbance to natural conditions. A cadastral map (locally known as a *mauza* map), prepared by Survey of Bangladesh, was used in locating the sediment accumulation monitoring sites, with their positions established by use of a Global Positioning System (GPS). The locations of the monitoring plots were selected using a stratified, systematic, unaligned sampling technique applied to the whole study area. Arrangements were made, with the co-operation of the landowners and local people, to leave monitoring plots fallow during the study period. A local person was then hired for five months (June to October) in 2007 and 2008 to look after the monitoring plots and ensure people or animals did not disturb them. This person was also responsible for recording inundation depths and durations for the whole flood season and for periodically collecting samples of floodwater for suspended sediment analysis.

4.4.3.2 Marker bed installation

There is no accepted method for monitoring the accumulation of flood-borne sediments in Bangladesh's floodplain. However, as mentioned earlier, FAP24 (1996) used three methods (soil coring, permeable mats and sediment traps) to measure floodplain sedimentation and their experience with these techniques was called on in the design of the present study. Based on the performance of different techniques reported by FAP24 (1996), the present study deployed a marker bed approach using permeable jute mats. This is essentially a slightly modified version of an approach first used by ISPAN (1995). 15 marker beds with dimensions 2 m × 2 m were constructed using locally available, permeable jute mats, plastic sheeting, iron nails, rope, wire and bamboo (Figure 4.4, Photograph 4.2 and Table 4.2).

Photograph 4.2 Marker bed installed to monitor the thickness of accumulated sediment

Table 4.2 Identification codes for Marker beds in the *Bara Bania Mauza* of the Jamuna floodplain

Sampling Location	Identification Codes	
	2007	**2008**
Natural levee	NLMB1_07, NLMB2_07, NLMB3_07, NLMB4_07, NLMB5_07, NLMB6_07	NLMB1_08, NLMB2_08, NLMB3_08, NLMB4_08, NLMB5_08, NLMB6_08
Back Slope	BSMB1_07, BSMB2_07, BSMB3_07, BSMB4_07, BSMB5_07, BSMB6_07, BSMB7_07	BSMB1_08, BSMB2_08, BSMB3_08, BSMB4_08, BSMB5_08, BSMB6_08, BSMB7_08
Back Swamp (*Beels)*	BSWMB1_07, BSWMB2_07	BSWMB1_07, BSWMB2_07

An iron rod marked in inches was placed in the centre of the marker bed so that if all of the apparatus was washed out by water flow then sediment deposition thickness could be measured based on that alone. A fence was put around the marker bed using bamboo and matting to keep floating vegetation out and so that the bed remained undisturbed by people and animals. The purpose of using plastic sheets beneath the jute mats was so that all deposited sediment could be separated from the in situ sediment. Permeable jute mats were used to reduce the effects of surface erosion, rain-drop splashing and for the capture of suspended sediment. In 2007, the marker beds were constructed between 15 and20 June. In 2008, they were constructed between 18 and 24 July. In both years, the beds were left in place for the entire duration of flood event (Photograph 4.3).

Photograph 4.3 Marker bed inundated during the summer flood

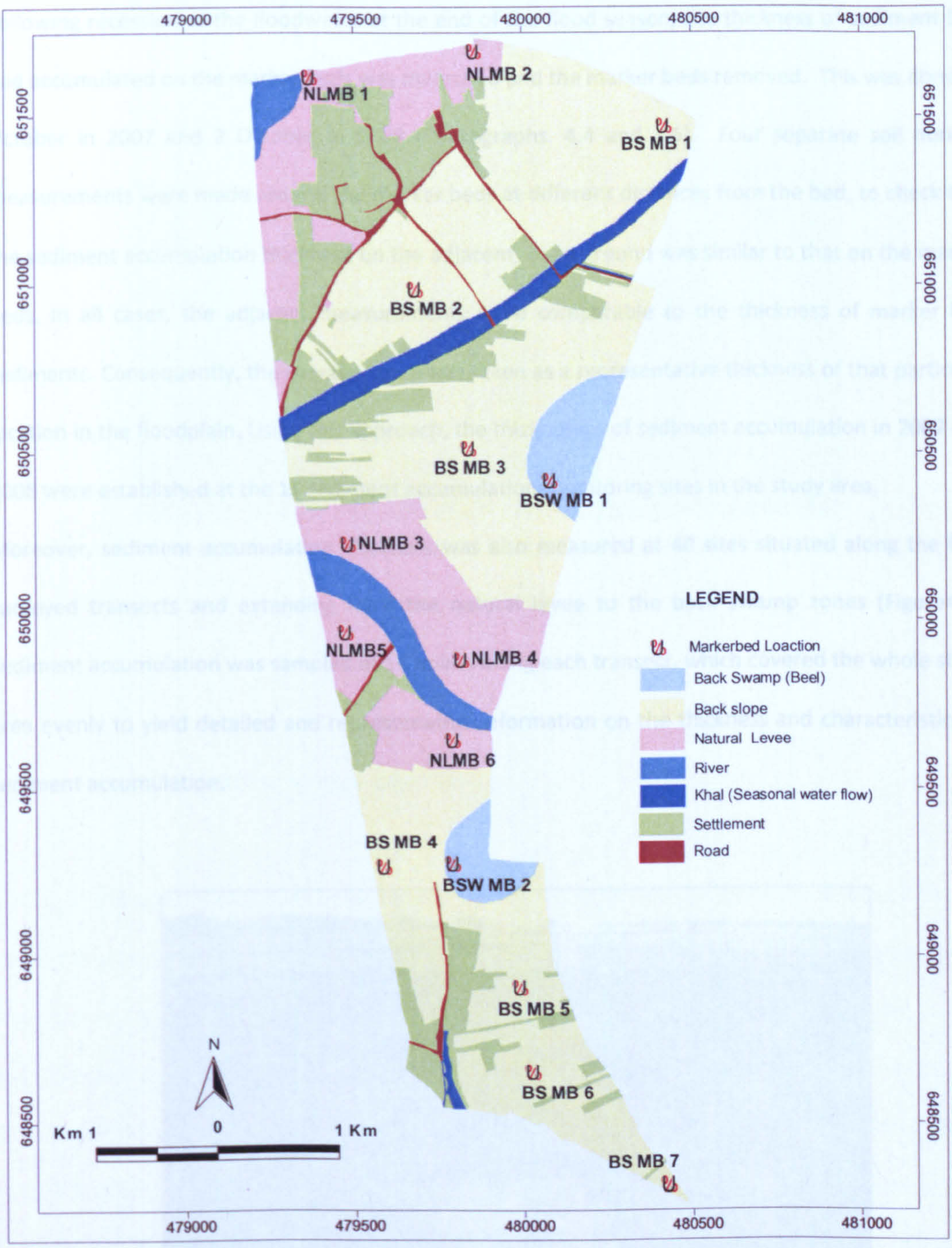


Figure 4.4 Marker beds used to measure sediment accumulation in the study area during the 2007 and 2008 summer monsoon floods

4.4.3.3 Measurement of sediment accumulation thickness

Following recession of the floodwater at the end of the flood season, the thickness of sediment that had accumulated on the marker beds was measured and the marker beds removed. This was done 25 October in 2007 and 2 October in 2008 (Photographs. 4.4 and 4.5). Four separate soil horizon measurements were made around the marker beds at different distances from the bed, to check that the sediment accumulation thickness on the adjacent, open ground was similar to that on the marker beds. In all cases, the adjacent measurements were comparable to the thickness of marker bed sediments. Consequently, the average value was taken as a representative thickness of that particular location in the floodplain. Using this approach, the thicknesses of sediment accumulation in 2007 and 2008 were established at the 15 sediment accumulation-monitoring sites in the study area.

Moreover, sediment accumulation thickness was also measured at 40 sites situated along the four surveyed transects and extending from the natural levee to the back swamp zones (Figure4.5). Sediment accumulation was sampled at 10 points along each transect, which covered the whole study area evenly to yield detailed and representative information on the thickness and characteristics of sediment accumulation.

Photograph 4.4 Sediment deposited on marker bed after floodwater recession

Photograph 4.5 Thickness of deposited sediment on marker bed

4.4.3.4 Deposition sediment sample collection

A total of 110samples of accumulated sediment were collected from between the sediment surface and depths ranging 1cm to 6cm in 2007 and 2008. The samples consisted of 15 samples from marker beds (one per marker bed) and 40 samples from sample sites along the surveyed transects in each year (Figure 4.5, Table 4.2 and Table 4.3). Each sample was taken as a composite of three sub-samples taken from the same sediment deposit in order to represent the range of grain sizes present at that location using the techniques proposed by Church and Kellerhals (1978), Dawson (1988), Robinson and Singerland (1998) and Islam (2006). A further 110 samples were also collected from the sediment accumulation sampling sites and retained as back-up samples following the approaches of Dawson(1988). All Samples were placed in heavy-duty polythene bags, sealed, labelled and transported to the University of Nottingham for particle size analysis by laser diffraction techniques in LS-Coulter 230.

Table 4.3 Identification codes for samples of accumulated sediment

Sampling Locations	Identification Codes					
	2007			2008		
Natural levee	DS01_07, DS08_07, DS20_07, DS24_07,	DS02_07, DS16_07, DS21_07, DS25_07,	DS05_07, DS17_07, DS23-07, DS26_07	DS01_08, DS08_08, DS20_08, DS24_08,	DS02_08, DS16_08, DS21_08, DS25_08,	DS05_08, DS17_08, DS23-08, DS26_08
Back slope	DS03_07, DS07_07, DS11_07, DS14_07, DS27_07, DS33_07, DS36_07, DS39_07,	DS04_07, DS09_07, DS12_07 DS18_07, DS29_07, DS34_07, DS37_07, DS40_07	DS06_07, DS10_07, DS13_07, DS22_07, DS32_07, DS35_07, DS38_07,	DS03_08, DS07_08, DS11_08, DS14_08, DS27_08, DS33_08, DS36_08, DS39_08,	DS04_08, DS09_08, DS12_08, DS18_08, DS29_08, DS34_08, DS37_08, DS40_08	DS06_08, DS10_08, DS13_08, DS22_08, DS32_08, DS35_08, DS38_08,
Back swamp*(Beels)*	DS15_07, DS30_07,	DS19_07, DS31_07,	DS28_07,	DS15_08, DS30_08,	DS19_08, DS31_08,	DS28_08,

4.4.4 Determination of sediment particle size distributions

In this study, all suspended (80) and accumulated samples (110) were analysed using a Beckman Coulter Laser Diffraction particle size analyser (LS-230) with 3 runs (3 minutes) per sample and with 20% of sample being re-analysed randomly to check the level of analytical consistency. Before putting the sediment samples into the Coulter counter instrument, samples were prepared using the following procedure. The samples were dried at 80^{0}C for 24 hours to remove moisture, disaggregated using a pestle and mortar and weighed. The samples were then passed through a series of stacked sieves with openings ranging from 500μm to 63μm.

It is important to mention here that 98% of samples passed through the 63μm sieve. The sediment finer than 63μm was treated with hydrogen peroxide for 24 hours and then put into the fume cupboard in a hot bath for 2 hours (the first hour at 60^{0}C and the second at 85^{0}C) to release water vapour. The samples were then set aside for a few hours to cool. Following this, the samples were washed out with distilled water using a centrifuge (at a speed at 3500rpm for 3 minutes and for at least three times). Calgon (Sodium hexametaphosphate and Sodium carbonate) was then added to disperse the particles.

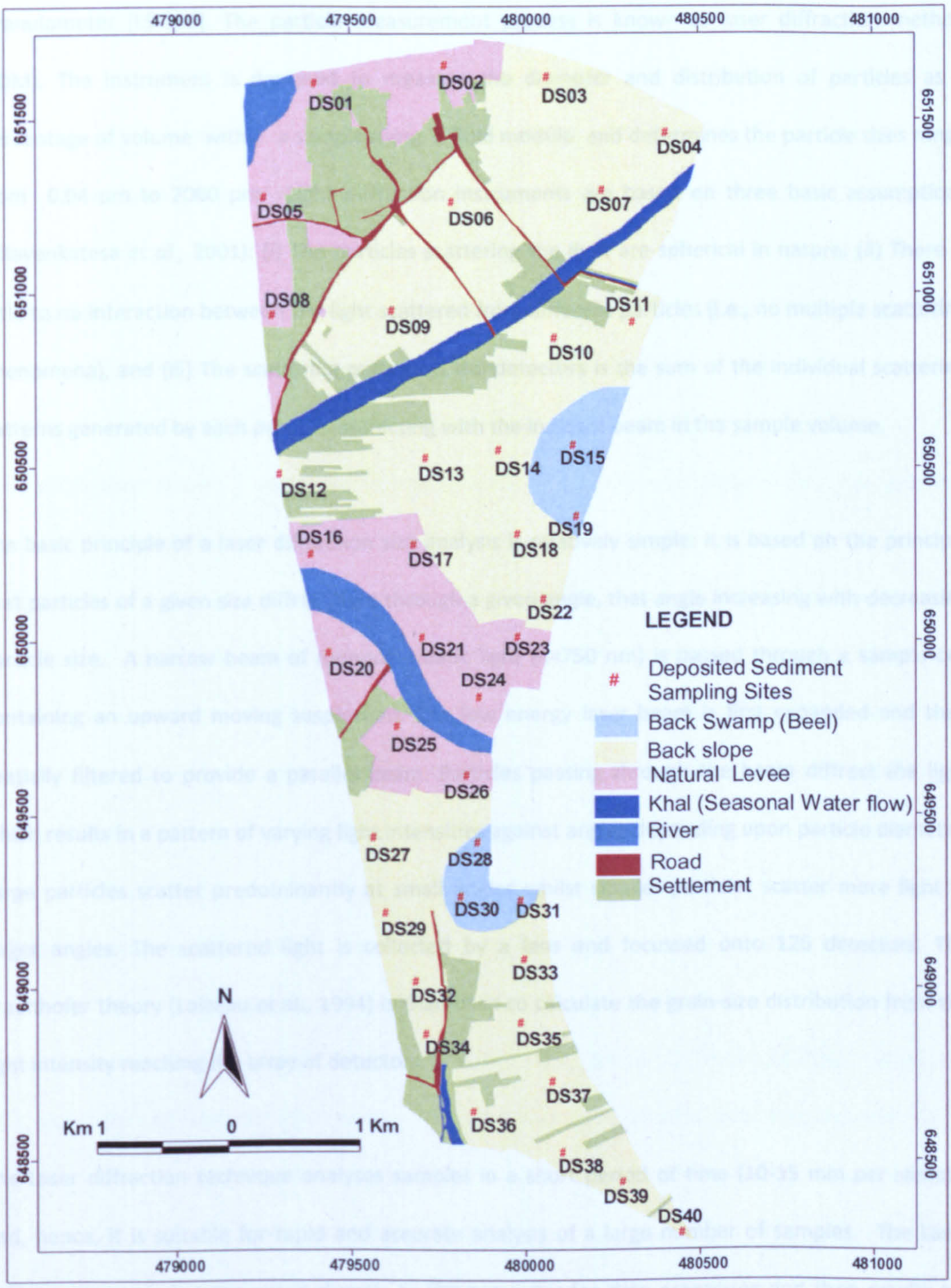


Figure 4.5 Sampling locations for accumulated sediments in the study area

After this preparation, the samples were analysed for particle size using the Coulter Laser Granulometer (LS-230). The particle measurement process is known as laser diffraction method (LDM). The instrument is designed to measure the diameter and distribution of particles as a percentage of volume within a sample using a fluid module and determines the particle sizes range from 0.04 μm to 2000 μm. Light diffraction instruments are based on three basic assumptions (Jillavenkatesa *et al.*, 2001): (i) The particles scattering the light are spherical in nature, (ii) There is little to no interaction between the light scattered from different particles (i.e., no multiple scattering phenomena), and (iii) The scattering pattern at the detectors is the sum of the individual scattering patterns generated by each particle interacting with the incident beam in the sample volume.

The basic principle of a laser diffraction size analysis is relatively simple. It is based on the principle that particles of a given size diffract light through a given angle, that angle increasing with decreasing particle size. A narrow beam of monochromatic light (λ=750 nm) is passed through a sample cell containing an upward moving suspension. The low energy laser beam is first expanded and then spatially filtered to provide a parallel beam. Particles passing through the beam diffract the light which results in a pattern of varying light intensities against angles depending upon particle diameter. Large particles scatter predominantly at small angles whilst smaller particles scatter more light at larger angles. The scattered light is collected by a lens and focussed onto 126 detectors. The Fraunhofer theory (Loizeau et al., 1994) is then used to calculate the grain-size distribution from the light intensity reaching the array of detectors.

The Laser diffraction technique analyses samples in a short period of time (10-15 min per sample) and, hence, it is suitable for rapid and accurate analysis of a large number of samples. The Laser detector response is transmitted directly to the computer for data processing and then results are displayed in the form of normal frequency and cumulative frequency curves including sediment size classes, and statistics of both central tendency and dispersion parameters, with diffusion values. As the laser diffraction method counts the particles ranging from 0.4μm to 2000μm, it therefore covers a wide range of grain sizes and all data are recorded in the computer in an Excel file format. Further, the stored data can be easily explored using statistics and trend analysis using Laser Sizes Control Program v-2.11 (Agrawal *et al.*, 1991; Bott and Hart, 1996).

4.5 Analysis and Results

4.5.1 Land form characteristics of the study area

The first step in generating the DEM was to calculate the average landform height variation of the study area, based on the levelling survey data. For this purpose, the Arc view GIS technique was used. The data was entered into an attribute table in an Arc view GIS environment so that it could be used as a point data source. Based on this point data, a DEM was produced using the available Geostatistical analyst tools (Figure 4.6). Several tools could be used to create the DEM, including inverse distance weighted, spline, kriging and natural neighbour analyses, each of which has positive and negative aspects. Considering the advantages and limitations of the alternatives, the kriging method was selected as most appropriate to the task of interpolating the landscape features. A semivariogram model was used to create the DEM. Raster calculator and natural breaks classification was used in Arc GIS spatial analyst system to clip the DEM according to the study area because the primary DEM appears in a rectangular. Figure 4.6 presents the elevation ranges from 10.66m+PWD to 14m+PWD, where m+PWD refer to the elevations in metres above the Public Works Datum that is used by the Survey of Bangladesh and Bangladesh Water Development Board (BWDB). Table 4.4 shows that the land surface height ranges in elevation from 10m to 14.20m above PWD. Within the area, about 55% of lands elevation ranges between 11.67m and 13.10m, 30% lying between 13.1m and 14m, while 15% lying between 10.66m and 11.67m. This suggests that medium height lands (55%, 11.67m and 13.10m) occupy the major area in the study site, therefore, that most inundation is likely to be in the 'moderate' flood depth range.

Table 4.4 Study site land elevation (m+PWD)

Land types	**Elevation (m+PWD)**			
	Field survey	**BWDB**	**Average**	**% of total land**
High land	13.90	14.00	13.95	30
Medium high land	12.80	13.00	12.90	55
Low land	11.17	12.00	11.60	10
Very low land	10.00	11.00	10.50	5

Based on the landform heights and field survey, the study area is composed mainly of elements of the active and young Jamuna floodplain. The landforms in it are consequently, evolving continuously in response to sediment processes involving both erosion and deposition. Sediment processes in the study area include lateral accretion and erosion associated with migration of the channel of the Jamuna River as well as vertical accretion and overbank scour during flood events. The scope of the field study was limited to investigating the contemporary rates, calibres, and spatial distribution of sediment accumulating vertically on the floodplain and they interrelate with terrain, land use, and floodplain landform characteristics. The starting point for establishing the relationship between landform heights and sedimentation is to produce a map of floodplain landforms. Hence, Arc GIS Geostatistical techniques were used to produce a landform height classification map, based on the elevation data collected in the levelling survey (Figure 4.7). Based on the map a ground checking was performed in the study site to identify the inundation level during the flood. The available information of the local farmers used to classify the land type height based on the flood depth. It should be mentioned here that the Bangladesh Soil Research and Development Institute (SRDI), Bangladesh Water Development Board (BWDB) and Survey of Bangladesh (SOB) use the flood level to classify land heights whether it is vulnerable to floods. The same procedure was used in this study to cross check the land height. The total area of the study site is 1289 hectares of which natural levees occupy nearly 50% of the study area with an area of 645 hectares. The areas of the other landforms in the area are back slopes, 258 hectares (20%); 193 hectares back swamps (*beels*), (15%) and rivers, 193 hectares (15%) (Table 4.5).

Table 4.5 Landform distribution of the study

Landform Types	Area (hectares)	Percentage
Natural Levee	645	50
Back slope	258	20
Back Swamp (*Beel*)	193	15
River	193	15
	1289	100

4.5.2 Flood inundation depths and durations

Floods were started in late June but available inundation observed from the middle of July in 2007 and 2008. Hence, maximum flood depth and duration are listed in Table 4.6 for the month of July, August and September for both years. Flood depth monitoring sites were selected on the marker bed where sediment accumulations were measured. Therefore, flood depth and duration observed at 15 different sites (6 at the natural levee, 7 at the back slope and 2 at the back swamps) during two-summer monsoon in 2007 and 2008.

This table also shows the total number of inundation days of each month of each site during monsoon 2007 and 2008. At the natural levee zones, the maximum floods depths were observed 2.20m and 1.10m in July, 2.55m and 1.50 in August, 2.35m, 1.25m in September, and total number of inundation days (average of six natural levee sites) were recorded 30 days and 22 days for 2007 and 2008 respectively. At the back slope zones (total 7 sites) the maximum flood depths were recorded 2.60m and 1.58m in July, 3.10m and 2.28m in August and 3.0m and 2.01m in September, and total number of inundation days (average of 7 back slopes sites) were recorded 45 days and 34 days for 2007 and 2008 respectively. At the back swamps zone (2 sites) the maximum flood depths were recorded 2.80m and 1.70m in July, 3.50m and 2.50m in August and 3.5m and 2.4m in September, and total number of inundation days (average of 2 back swamps sites) were recorded 60days and 45days for 2007 and 2008 respectively. The above records state that natural levee zone was the lower flood inundation depth and period, while higher in back swamps zone and the back slope was the moderate for the both years.

Considering the spatial variability between landforms, the minimum flood depths were observed at the natural levees (1.50m on 16 July and 24 September in 2007 and 0.6m on 16 July in 2008), while the maximum flood depths were observed in back swamps (3.50m on 15 August and 14 September in 2007 and 2.5m on 15 August in 2008). Depths in the back slope area were intermediate. However, there was considerable variability within each of the landforms. For example, the minimum and maximum flood depths were measured within the natural levee zone 1.5m and 2.50m in 2007, and 0.6m and 1.50m in 2008. In the back slope landform zone, minimum and maximum ranged from 1.8m to 2.80m in 2007 and from 0.70m to 1.70m in 2008, while it ranged from 2.00m to 3.50m in 2007 and 1.60m to 2.40m in 2007 for the back swamps (Table 4.7).

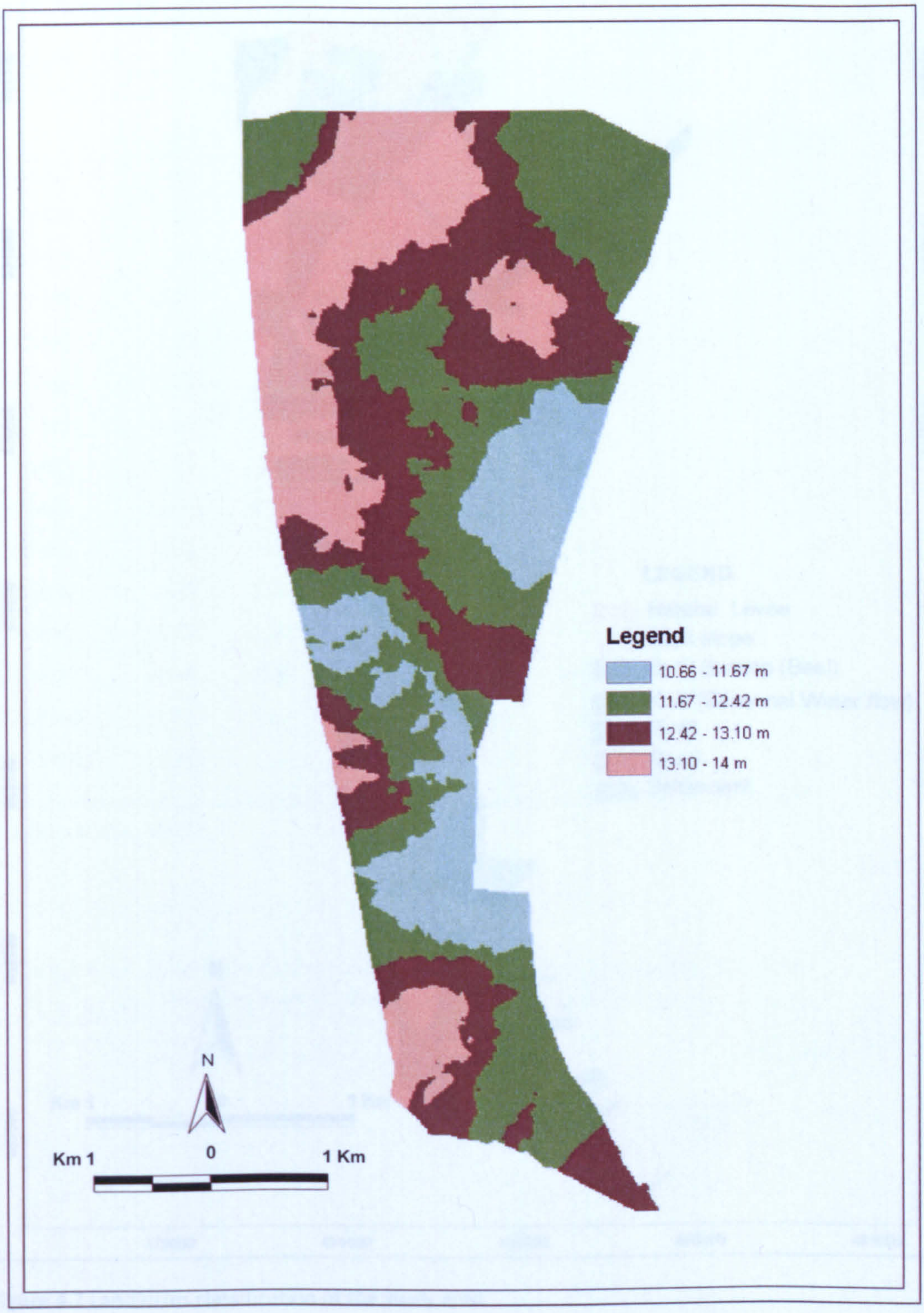


Figure 4.6 Landform height variations of the study area

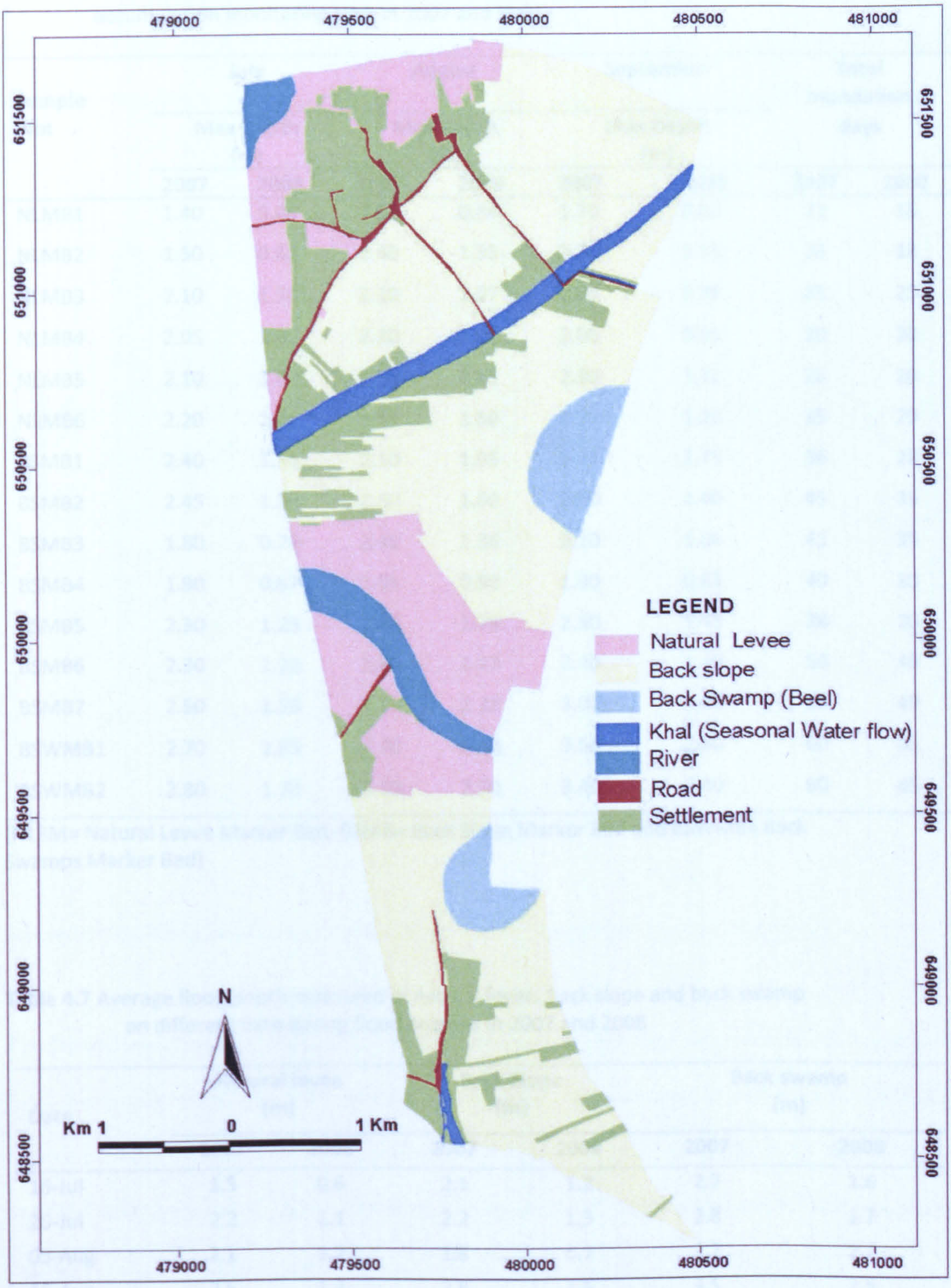


Figure 4.7 Landforms classification of the study area

Table 4.6 Maximum inundation depths and total durations observed at the sediment accumulation monitoring sites in 2007 and 2008

Sample Plot	July		August		September		Total Inundation days	
	Max Depth (m)		Max Depth (m)		Max Depth (m)			
	2007	2008	2007	2008	2007	2008	2007	2008
NLMB1	1.40	0.46	1.90	0.84	1.70	0.64	22	16
NLMB2	1.50	0.61	2.40	1.35	2.20	1.15	25	18
NLMB3	2.10	1.10	2.10	1.07	2.00	0.98	35	25
NLMB4	2.05	1.05	2.10	1.06	2.00	0.95	30	20
NLMB5	2.10	1.02	2.50	1.45	2.30	1.22	28	20
NLMB6	2.20	1.04	2.55	1.50	2.35	1.25	35	29
BSMB1	2.40	1.31	2.10	1.05	2.75	1.75	36	28
BSMB2	2.45	1.38	2.50	1.60	2.50	1.40	45	35
BSMB3	1.80	0.76	2.40	1.36	2.10	1.06	45	35
BSMB4	1.90	0.67	1.95	0.90	1.90	0.81	40	30
BSMB5	2.30	1.23	2.80	1.78	2.50	1.45	38	30
BSMB6	2.30	1.22	2.80	1.77	2.40	1.40	50	40
BSMB7	2.60	1.58	3.10	2.28	3.00	2.01	55	40
BSWMB1	2.70	1.65	3.20	2.40	3.50	2.30	60	45
BSWMB2	2.80	1.70	3.50	2.50	3.40	2.40	60	45

[NLBM= Natural Levee Marker Bed, BSMB= Back Slope Marker Bed and BSWMB= Back Swamps Marker Bed]

Table 4.7 Average flood depth measured in natural levee, back slope and back swamp on different date during flood seasons in 2007 and 2008

Date	Natural levee (m)		Back Slope (m)		Back swamp (m)	
	2007	2008	2007	2008	2007	2008
16-Jul	1.5	0.6	2.1	1.2	2.7	1.6
26-Jul	2.2	1.1	2.2	1.3	2.8	1.7
05-Aug	2.1	1.2	1.8	0.7	3.2	2.2
15-Aug	2.5	1.4	2.8	1.5	3.5	2.5
25-Aug	2.2	1.5	2.5	1.3	3.2	2.1
04-Sep	2	0.9	2.4	1.4	3.4	2.1
14-Sep	2.4	1.2	2.8	1.7	3.5	2.4
24-Sep	1.5	1.3	2.2	1.4	2	1.9

This result also suggests that the higher inundation occurred in 2007 than 2008. However, comparing the two monsoon floods depth of 2007 and 2008 it reveals that the higher flood depth occurred at the back swamp zones in 2007 and lower depth observed at the natural levee in 2008(Figure 4.8).

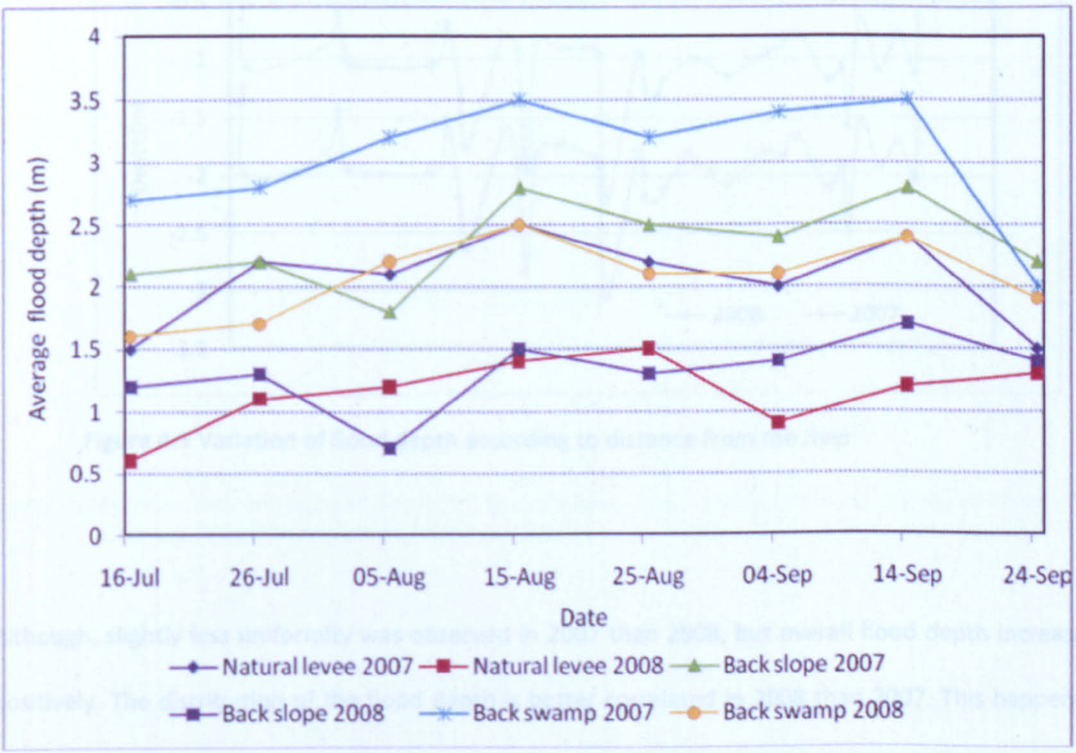


Figure 4.8 Flood depth variations at the different landforms in 2007 and 2008 monsoons

Flood depth variation occurred as a function of distance from the river and the trend of variation of flood depth more or less the same both in 2007 and 2008 monsoon flood, though a higher depth was recorded in 2007 compared to that in 2008 (Figure 4.9). In most of the cases, the flood depth was low near the river because of higher landform and higher flood depth occurred far away from the channel.

Figure 4.10 allows direct comparison of inundation depth variations for two summer monsoons of 2007 and 2008. It is evident from the observed records that positive correlations exist between flood inundation depth with the distance from the river for both monsoons of 2007 and 2008.

Figure 4.9 Variation of flood depth according to distance from the river

Although, slightly less uniformity was observed in 2007 than 2008, but overall flood depth increased positively. The distribution of the flood depth is better correlated in 2008 than 2007. This happened because 2007 floods were the catastrophic floods and the flood depth varied abnormally but in 2008, it varied more normally.

The residual plot (Figure 4.11 and 4.12) has been drawn using regression analysis to present the variation between the variables of inundation depth and distance for 2007. This result also suggests that the observed value distributed randomly and there is a huge residual variation in most of the cases. A variety of graphs and statistics reveal that the inundation depth actually varies with distance from the river and the minimum depth has a short duration at the natural levee and the maximum depth has a long duration at back swamps. This happened due to spatial variation in land elevation or water surface elevation.

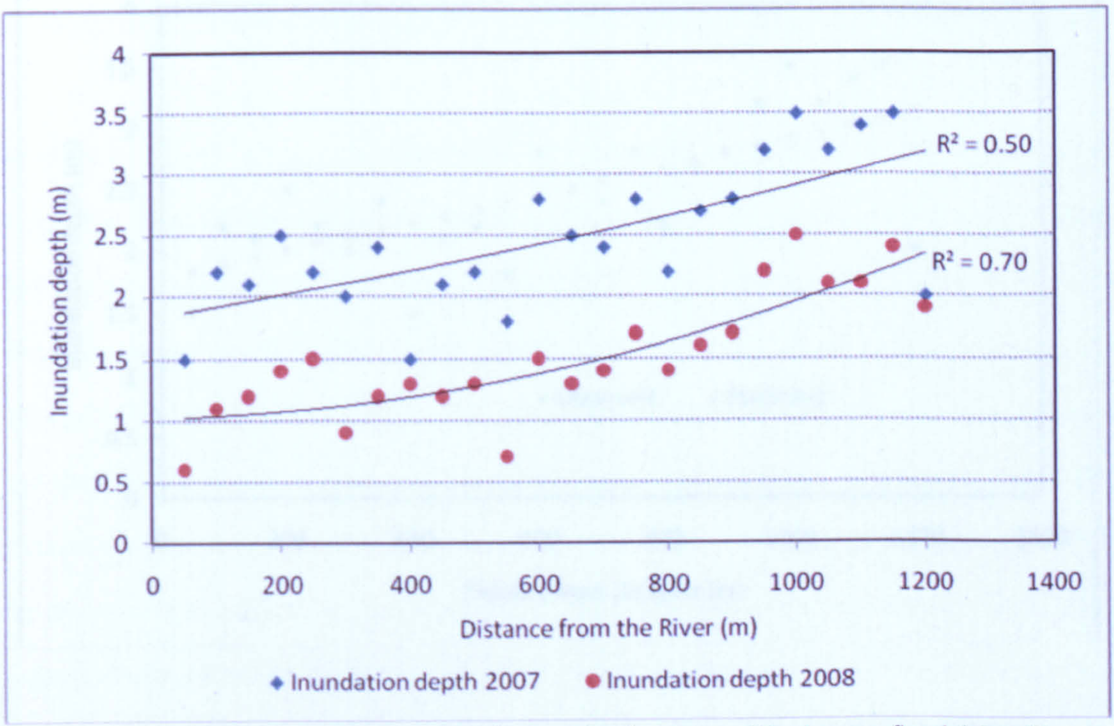


Figure 4.10 Variation in inundation depth in the *Bara Bania mauza* of the Jamuna floodplain with distance from the river for 2007 and 2008

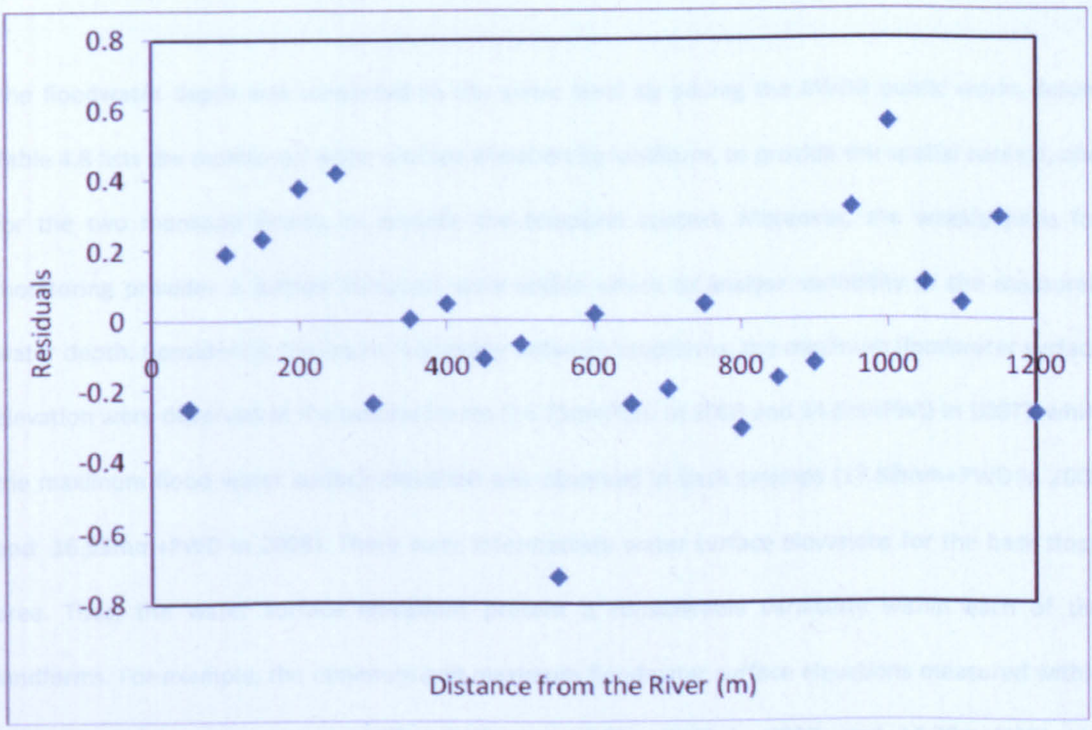


Figure 4.11 Residual plot of Distance and Inundation depth of 2007

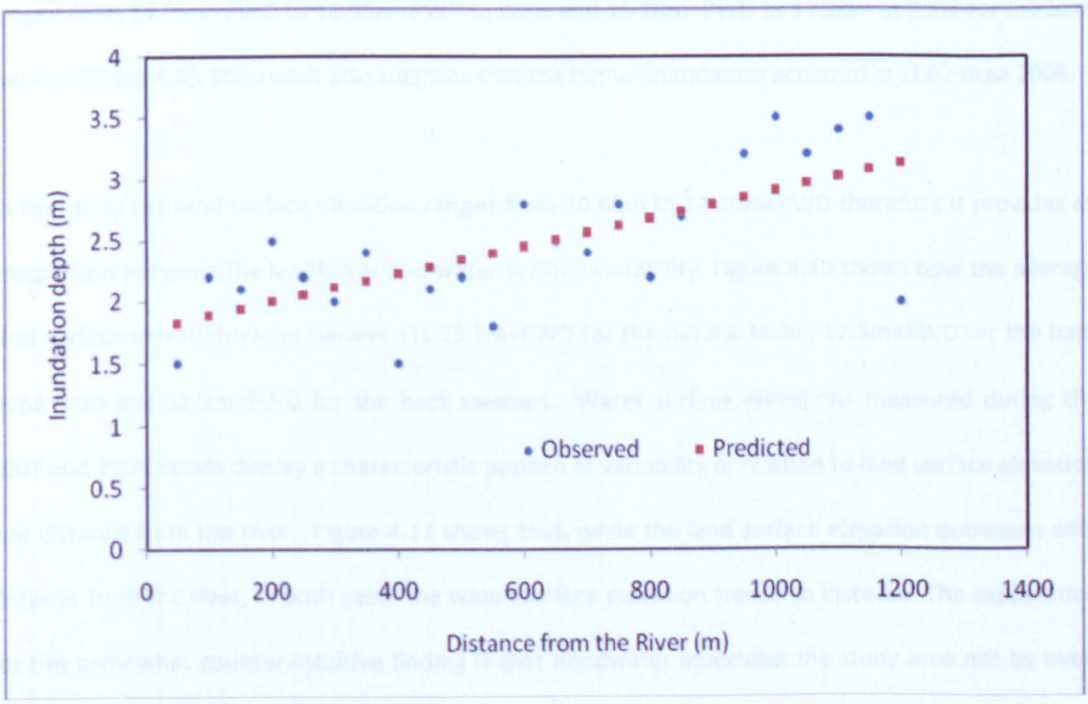


Figure 4.12 Variation between observed and predicted depth according to distance of 2007.

4.5.3 Spatial and temporal variation of water surface elevation

The floodwater depth was converted to the water level by adding the BWDB public works datum Table 4.8 lists the monitored water surface elevation by landform, to provide the spatial context, and for the two monsoon floods, to provide the temporal context. Moreover, the weekly basis for monitoring provides a further temporal scale within which to analyse variability in the measured water depth. Considering the spatial variability between landforms, the minimum floodwater surface elevation were observed at the natural levees (14.75m+PWD in 2008 and 14.8m+PWD in 2007), while the maximum flood water surface elevation was observed in back swamps (17.80mm+PWD in 2007 and 16.95mm+PWD in 2008). There were intermediate water surface elevations for the back slope area. Thus, the water surface elevations present a considerable variability within each of the landforms. For example, the minimum and maximum floodwater surface elevations measured within the natural levee area were 14.75m+PWD and 16.80m+PWD in 2007, and 14.30m+PWD and 15.91m+PWD in 2008. In the back slope landform zone, minimum and maximum ranged from 14.95m+PWD to 16.90m+PWD in 2008 and from 15.10m+PWD to 17.70m+PWD in 2007, while it ranged from 14.05m+PWD to 16.95m+PWD in 2008 and 15.20m+PWD to 17.80m in 2007 for the back swamps (Table 4.8). This result also suggests that the higher inundation occurred in 2007 than 2008.

As the study site land surface elevation ranges from 10.66m to 14.20m+PWD therefore it provides an comparison between the landforms and water surface variability. Figure 4.13 shows how the average land surface elevation varies between is 13.5m+PWD for the natural levee, 12.5m+PWD for the back slope area and 11.9m+PWD for the back swamps. Water surface elevations measured during the 2007 and 2008 floods display a characteristic pattern of variability in relation to land surface elevation and distance from the river. Figure 4.13 shows that, while the land surface elevation decreases with distance from the river, in both years the water surface elevation trends to increase. The explanation for this somewhat counter-intuitive finding is that floodwater inundates the study area not by over-topping the natural levee but via distributaries and intermittent channels (Khals). Thus, water spreads from the beels and up the back slope flowing (and sloping) towards the levee zone of the floodplain. When the water surface elevation overtops the natural levee, floodplain merges with that in the main channel. As the ground elevation of the natural levee the highest, while the water surface elevation there is the lowest, inundation depths are a minimum there. Also, during over bank flows, the levee area has the highest flow velocities because it is the closest to the main channel and has the steepest water surface slope. Conversely, the low elevation land in the back swamp area has the highest water surface elevations but the lowest velocities. Figure 4.13 also shows that the water surface elevation was higher in 2007 than 2008, although the same trend is evident in the water surface elevations, which vary as a positive function of the distance from the river. It is significant to note that, although the study site is a relatively small area and with low relief (the change in ground surface elevation across the area is just 1.6 m, flood dynamics produce a change in water surface elevation of about 1m over the same distance.

Figure 4.14 and 4.15 display the temporal variation in water levels for the three-landform zones in 2007 and 2008 based on the data in Table 4.8. It is evident that the hydrographs for the two floods differ substantially in several important respects. One is abnormal flood in 2007 and another is normal flood in 2008 which are locally known as *Bonna* and *Barsha* respectively. The flood water level started rising on 20 July for both years. In 2007, there were two high water level peaks recorded on 15 August and 14 September for the natural levee, back slope and back swamp zones, while, only one highest water level peak was recorded on 8 September in 2008 for the same landforms zones.

Table 4.8 Water levels (m+PWD=14m) at the monitoring sites during the summer monsoons of 2007 and 2008

Date	Natural levee (m+PWD)		Back Slope (m+PWD)		Back swamp (m+PWD)	
	2008	2007	2008	2007	2008	2007
20-July	14.30	14.90	14.95	15.10	15.05	15.20
27-July	14.84	15.50	15.84	16.50	15.90	16.60
03-Aug	14.88	15.70	15.90	16.60	15.95	16.65
10-Aug	15.00	15.80	16.00	16.85	15.10	16.90
17-Aug	15.31	16.80	15.20	17.70	15.35	17.80
24-Aug	15.50	15.75	15.70	16.50	15.85	16.65
31-Aug	15.66	14.75	16.70	15.90	15.80	15.95
08-Sep	15.91	14.90	16.90	15.80	15.95	15.85
15-Sep	15.55	16.75	16.70	15.50	15.75	17.45
22-Sep	15.25	15.00	15.50	16.10	15.55	16.20
29 Sep	14.91	14.30	15.10	15.20	15.15	15.50

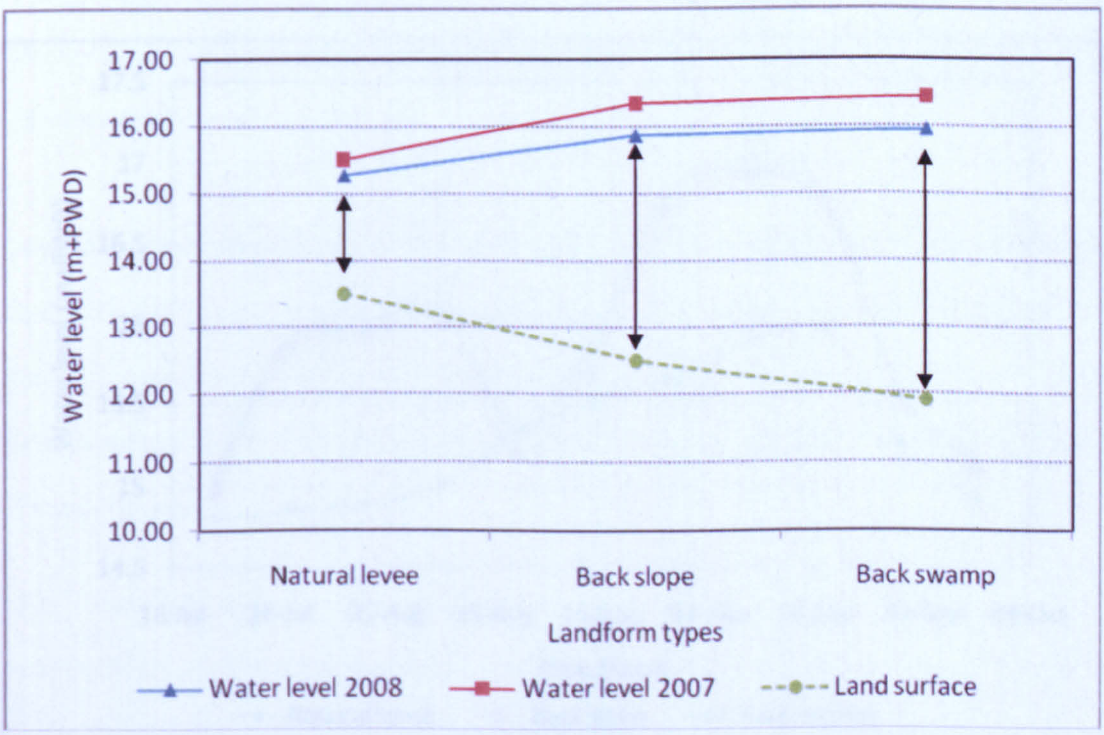


Figure 4.13 Variation in flood elevation with distance from river of the *Bara Bania* Village of the Jamuna Floodplain in Bangladesh in 2007 and 2008

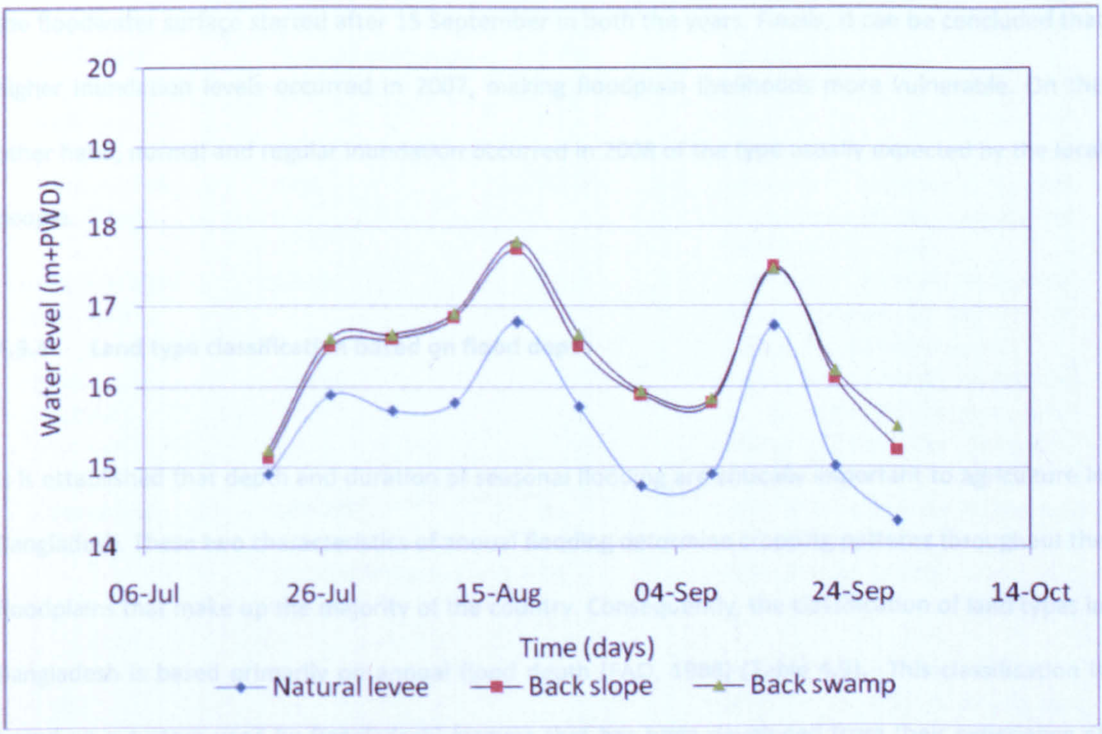


Figure 4.14 Flood water levels in the natural levee, Back slope and back swamp zones in 2007

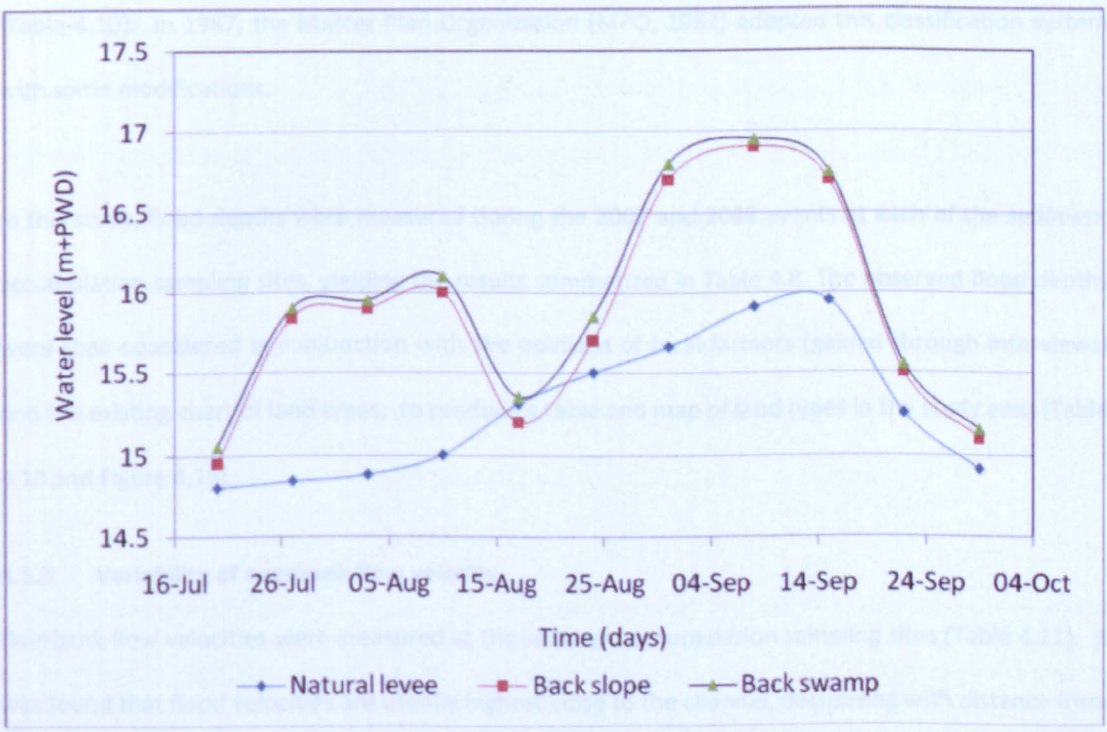


Figure 4.15 Flood water levels in the natural levee, Back slope, and back swamp zones in 2008

It also shows a lower water level in 2008 than in 2007 for all three landforms zones. The recession of the floodwater surface started after 15 September in both the years. Finally, it can be concluded that higher inundation levels occurred in 2007, making floodplain livelihoods more vulnerable. On the other hand, normal and regular inundation occurred in 2008 of the type usually expected by the local people.

4.5.4 Land type classification based on flood depth

It is established that depth and duration of seasonal flooding are critically important to agriculture in Bangladesh. These two characteristics of annual flooding determine cropping patterns throughout the floodplains that make up the majority of the country. Consequently, the classification of land types in Bangladesh is based primarily on annual flood depth (FAO, 1988) (Table 4.9). This classification is based on a system used by Bangladeshi farmers that has been developed from their experience of expected depths during the 'normal' floods, which determine the crop they grow on their various plots of land during the monsoon season. The depth-based classification has been further developed based on the country's reconnaissance soil surveys and agro-ecological zones (AEZs) (FAO, 1988) (Table 4.10). In 1987, the Master Plan Organization (MPO, 1987) adopted this classification system with some modifications.

In this study, flood depths were measured during the 2007 and 2008 events at each of the sediment accumulation sampling sites, yielding the results summarized in Table 4.8. The observed flood depths were then considered in conjunction with the opinions of local farmers (gained through interviews) and the existing chart of land types, to produce a table and map of land types in the study area (Table 4.10 and Figure 4.16).

4.5.5 Variability of overbank flow velocity

Overbank flow velocities were measured at the sediment accumulation sampling sites (Table 4.11). It was found that flood velocities are usually highest close to the channel, decreasing with distance from the main river.

Table 4.9 Standardized land types based on depth of flooding the country's reconnaissance soil survey and its agro-ecological zones

Land type (AEZ Classification)	Normal-maximum water Depth (cm)	MPO Classification	Description
High land (H)	0	F0	Land which is above normal flood level
Medium high land (MH)-1	0-30	F0	Land which normally is flooded up to about 30 cm deep during the monsoon season
Medium high land (MH)-2	30-90	F1	Land which normally is flooded up to between 30 and 90 cm during the monsoon season
Medium low land (ML)	90-180	F2	Land which normally is flooded up to between 90 cm and 180cm during the monsoon season
Low land (L)	180-300 (flooded<9 months)	F3	Land which normally is flooded up to 180cm and 300 cm during the monsoon season
	180-300 (flooded > 9 months)	F4	
Very low land (VL)	>300	F4	Land which normally is flooded deeper than 300 cm during the monsoon season
Bottomland	Mainly>300, but includes perennially wet	F4	Depression land in any of the above land types which remains wet through the year

Source: MPO, (1987) and FAO, (1988)

The observations made during this study concur with this general finding in that velocities were highest (just over 1m/s in both 2007 and 2008) in the natural levee area, which is adjacent to the channel of the Jamuna River, decreasing to minimum of 0.20m/s (in 2007) and was 0.17m/s (in 2008) in the back swamps (*beels*). These results suggest that larger grain sizes and thicker accumulations of flood sediment should be expected on the natural levees and than in the back swamps. It also suggests that higher flow velocities may be responsible for wider size ranges in deposited sediment (moderate to poorly sorted) in levee areas, while the ranges of size in sediment deposited in areas with lower velocities should be smaller (well sorted).

The velocity was very high in 2007 compared to 2008, because there was a large flood in 2007 and a normal flood in 2008. The common trend observed for both years was that the velocity profiles were high at the natural levees and gradually got lower toward the back swamp area (Figure 4.17). The velocity was also found to be high in seasonal flowing creeks, which are locally known as *Khal.*

Table 4.10 Study area land types, local names and their common uses.

Land type & soil broadly	Local Name	Inundation	No. of Plot	Area (hectares)	Common uses
High land (Friable Silty and clay	*Chala/ Taan*	Flood free	482	201	Settlement
Medium high land, Friable silty and clay	*Tek/ Nal*	Flood free	598	450	Settlement, road, Periodic Market(*Hat)*
Medium low land Sandy loam	*Kanda*	0-1 months	771	400	Agriculture
Low land	*Byde (Baid)*	3-5 months	140	90	Agriculture (*Boro* paddy*)*
Very low land	*Beel & Nadi* (River)	6-7 months	339	148	Fishing, irrigation, Agriculture

Sources: Observed inundation depths and Interviews performed during fieldwork in 2007 and 2008

Table 4.11 Overbank flow velocities observed in 2007 and 2008

Sample sites	Average velocity (m/s)		
	2007	2008	Average
NLMB1	1.02	0.89	0.96
NLMB2	0.59	0.46	0.53
NLMB3	1.02	0.95	0.99
NLMB4	1.03	0.96	1.00
NLMB5	1.04	0.98	1.01
NLMB6	1.00	0.92	0.96
BSMB1	0.36	0.29	0.33
BSMB2	0.45	0.39	0.42
BSMB3	0.59	0.51	0.55
BSMB4	0.57	0.50	0.54
BSMB5	0.29	0.27	0.28
BSMB6	0.33	0.30	0.32
BSMB7	0.28	0.21	0.25
BSWMB1	0.20	0.19	0.20
BSWMB2	0.21	0.17	0.19

4.5.6 Particle Size Characteristics of Accumulated Sediments

Particle size characteristics provide a record of the fluvial depositional environment. A number of researchers have used particle size to interpret past environments (Paola *et al.*, 1992; Livingstone *et al.*, 1999) and reconstruct the environmental dynamics during the period over which the sediments accumulated (McCave and Syvitski, 1991; Church, 1999). This section presents the results of Particle Size Analyses (PSA) using laser diffraction methods and computer analysis, and describes the sedimentary characteristics of the Brahmaputra-Jamuna river floodplain in the study area to establish the mode of sediment deposition Several scales are commonly used for the description and analysis of particle size distributions. Most practical applications use logarithmically-distributed size classes expressed in ϕ (phi), millimetre or micrometer (μm) units. This is related to the fact that most samples from fluvial, sedimentary deposits display a near normal distribution when divided into logarithmic size classes. In this study, the frequencies of measured sizes of sediment particles (in micrometres (μm)) were grouped into nine, logarithmic classes according to the Wentworth scale. (Table 4.12).

4.5.6.1 Suspended sediment concentrations

A total of 40 suspended sediment-sampling sites were each sampled 4 times. The average sediment concentration measured at each site was used to represent that sampling point. Thus, total 40 samples (40 × 1 average per point) were collected each year, yielding a total 80 samples for two years that were analysed using the laser diffraction analyser. Sample locations were distributed between the different landform zones (see Table 4.1 and Figure 4.3). Hence, the samples were split between the natural levee (9 for each year), back slope (20 for each year), back swamps (6 for each year) and seasonally flowing, floodplain channels known as *khals* (5 for each year). The measured concentrations of suspended sediment are listed in Table 4.13. The results indicate that suspended sediment concentrations tend to decrease with distance from the river although there is no statistically significant correlation (Figure 4.18).

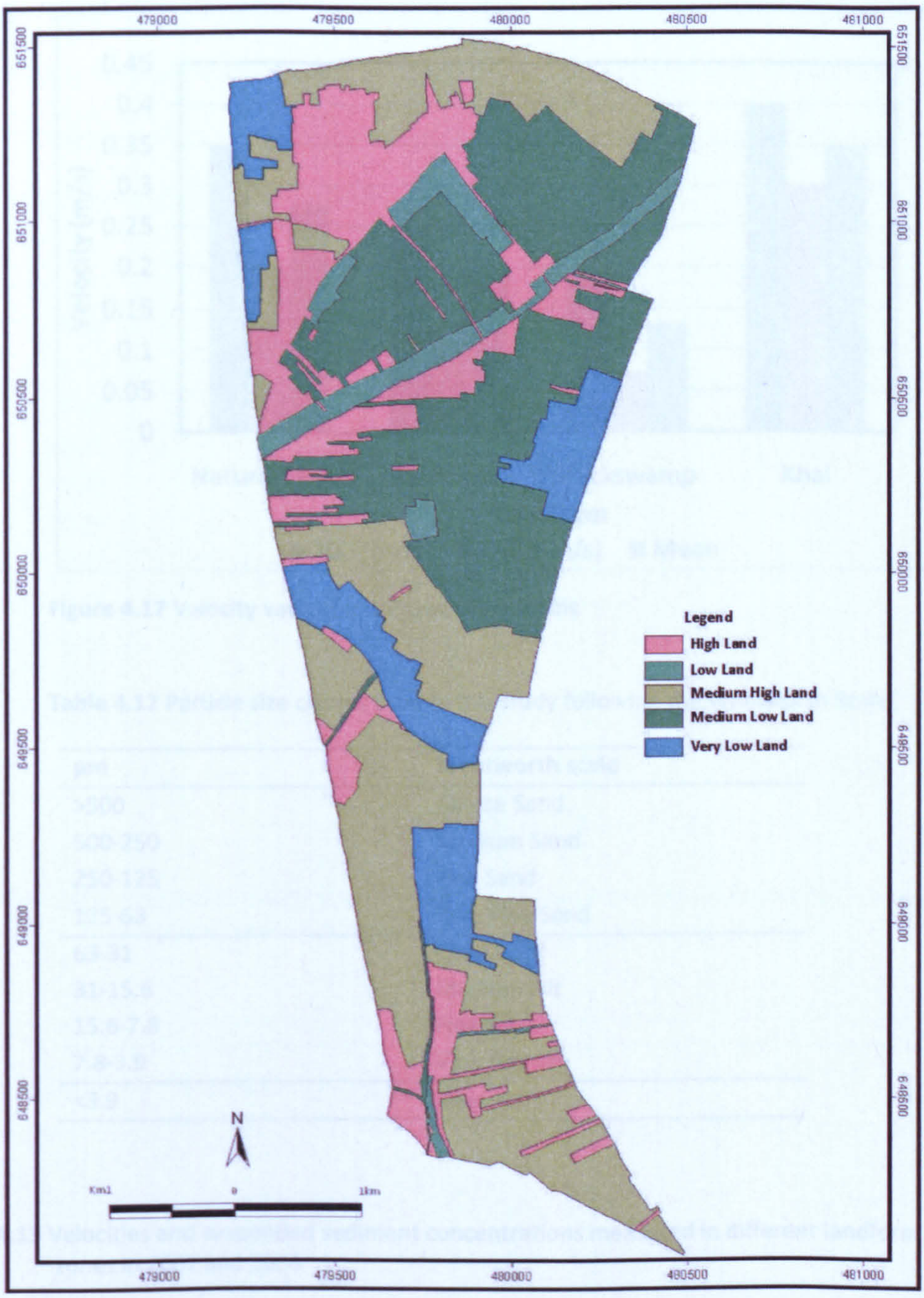


Figure 4.16 Land type classifications based observed inundation depths, local farmers' opinions and the existing chart of land types

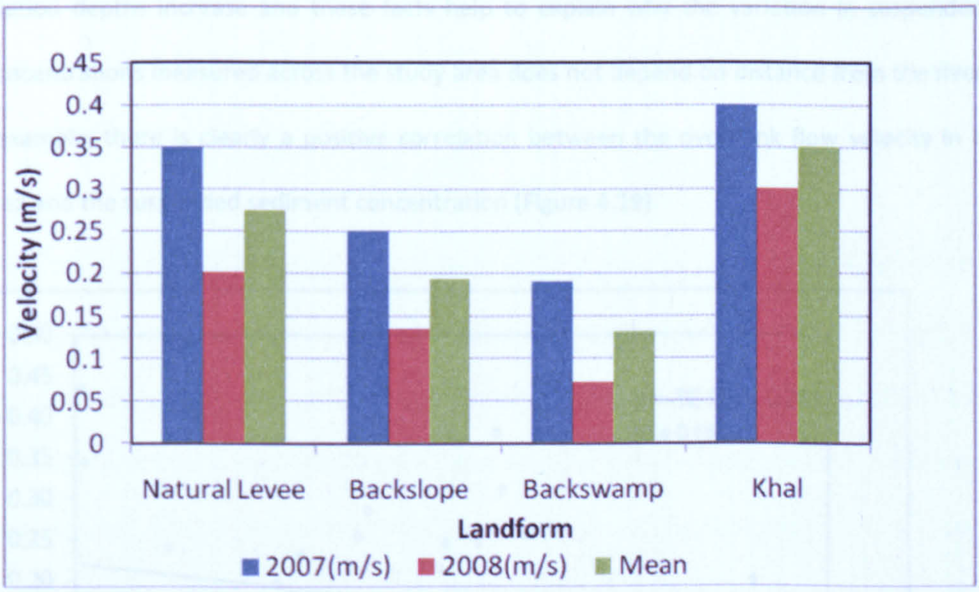


Figure 4.17 Velocity variations between landforms

Table 4.12 Particle size classes used in this study following the Wentworth Scale

µm	Wentworth scale
>500	Coarse Sand
500-250	Medium Sand
250-125	Fine Sand
125-63	Very Fine Sand
63-31	Coarse Silt
31-15.6	Medium Silt
15.6-7.8	Fine Silt
7.8-3.9	Very fine silt
<3.9	Clay

Table 4.13 Velocities and suspended sediment concentrations measured in different landform zones in 2007 and 2008

Landforms	Velocity (m/s)		Suspended Sediment (g/l)		Average velocity (m/s)	Average sediment concentration (g/l)
	2007	2008	2007	2008		
Natural levee	0.35	0.20	4.25	3.95	0.28	4.10
Back slope	0.25	0.14	2.55	1.90	0.20	2.23
Back swamp	0.19	0.07	1.65	1.25	0.13	1.45
Khal	0.40	0.30	4.20	3.80	0.35	4.00
Average	0.30	0.18	3.16	2.73	0.24	2.94

It is pointed out in section 4.5.5 that overbank flow velocities decrease with distance from the river, while inundation depths increase and these facts help to explain why the variation in suspended sediment concentrations measured across the study area does not depend on distance from the river alone. For example, there is clearly a positive correlation between the overbank flow velocity in a landform area and the suspended sediment concentration (Figure 4.19).

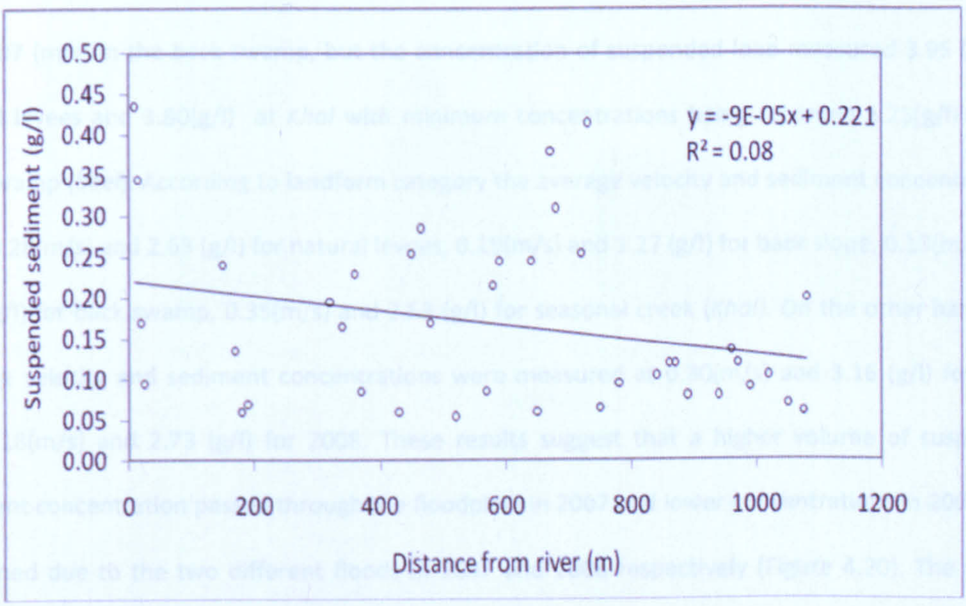


Figure 4.18 Relation between suspended sediment concentrations and distance from river (average of 2007 and 2008)

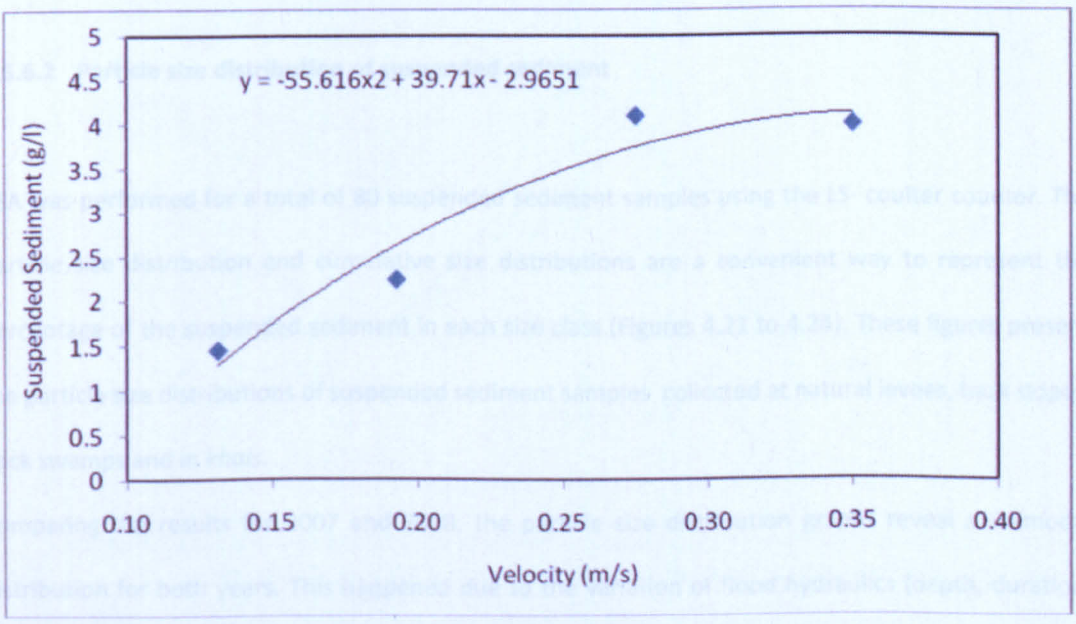


Figure 4.19 Relation between velocity and suspended sediment concentrations (average of 2007 and 2008)

Measured concentrations of suspended sediment were in fact highest at the natural levee (4.25g/l) and in the *khal* channels crossing the floodplain (4.20g/l) during the 2007 flood peak period. Concentrations were much lower at that time in the back swamps *(beels)* areas (1.65g/l). This spatial pattern was similar in 2008.

The highest velocity was 0.30(m/s) at *Khal* and 0.25(m/s) at the natural levees and the lowest velocity was 0.07 (m/s) in the back swamp, but the concentration of suspended load measured 3.95 (g/l) at natural levees and 3.80(g/l) at *Khal* with minimum concentrations being recorded 1.25(g/l) at the back swamp (*beel*). According to landform category the average velocity and sediment concentrations were 0.28(m/s) and 2.63 (g/l) for natural levees, 0.19(m/s) and 1.27 (g/l) for back slope, 0.13(m/s) and 0.83 (g/l) for back swamp, 0.35(m/s) and 2.53 (g/l) for seasonal creek (*Khal)*. On the other hand, the average velocity and sediment concentrations were measured at 0.30(m/s) and 3.16 (g/l) for 2007 and 0.18(m/s) and 2.73 (g/l) for 2008. These results suggest that a higher volume of suspended sediment concentration passed through the floodplain in 2007 and lower concentrations in 2008. This happened due to the two different floods in 2007 and 2008 respectively (Figure 4.20). The overall scenario of the velocity and suspended sediment concentrations for the two monsoon flood was 0.24(m/s) and 1.82 (g/l).

4.5.6.2 Particle size distribution of suspended sediment

PSA was performed for a total of 80 suspended sediment samples using the LS- coulter counter. The particle size distribution and cumulative size distributions are a convenient way to represent the percentage of the suspended sediment in each size class (Figures 4.21 to 4.24). These figures present the particle size distributions of suspended sediment samples collected at natural levees, back slopes, back swamps and in *khals*.

Comparing the results for 2007 and 2008, the particle size distribution graphs reveal a unimodal distribution for both years. This happened due to the variation of flood hydraulics (depth, duration, velocity). The particle size distribution of 2008 followed the average trend more than the 2007. The different symmetrical pattern of 2007 represents the high variability of flood hydraulics because in that year a large flood occurred.

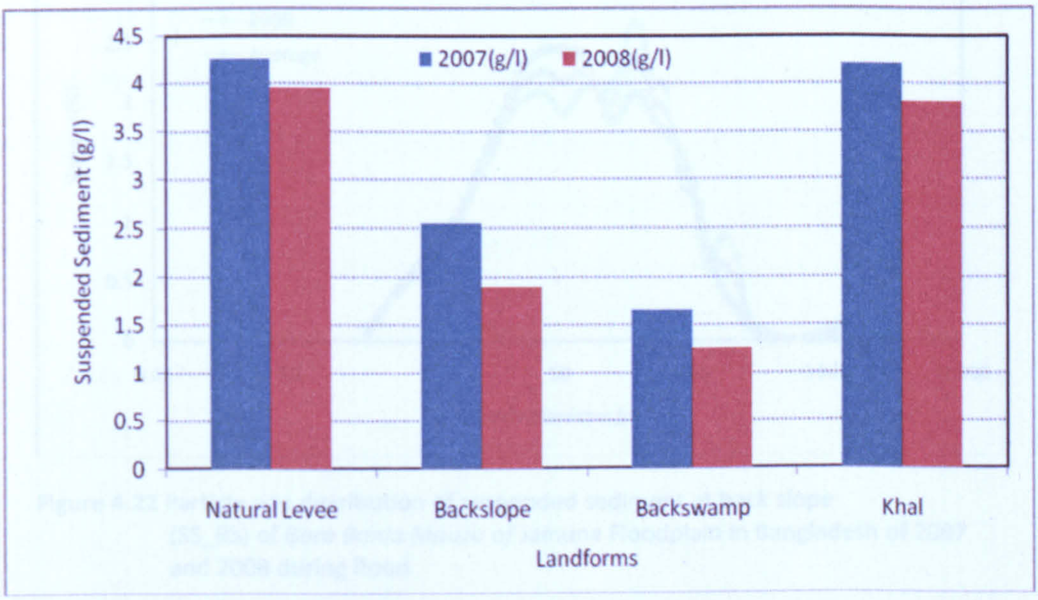


Figure 4.20 Variation between suspended sediment concentrations depending on landforms

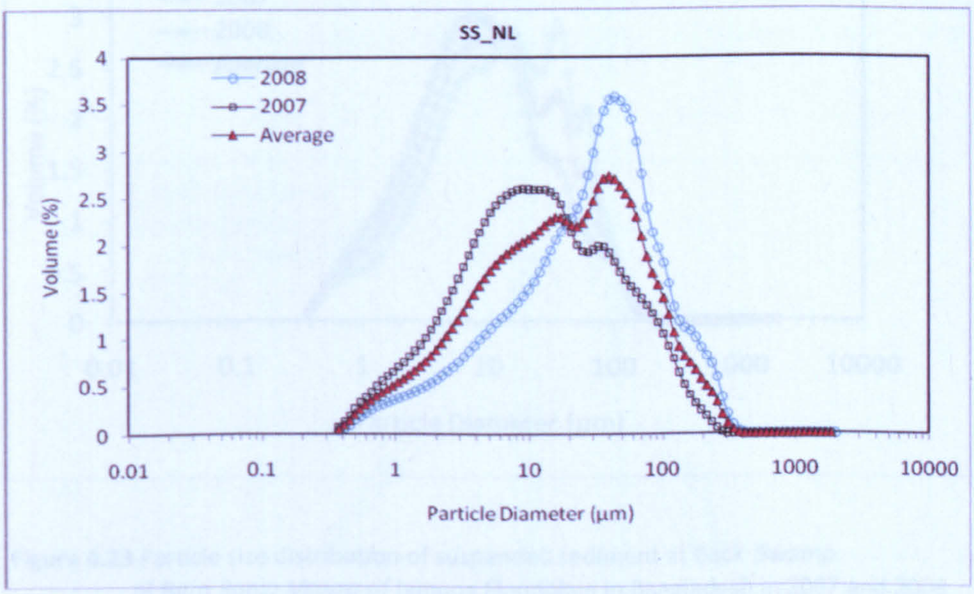


Figure 4.21 Particle size distribution of suspended sediment measured at the natural levee (SS_NL) of *Bara Bania Mauza of* Jamuna Floodplain in Bangladesh of 2007 and 2008 during flood

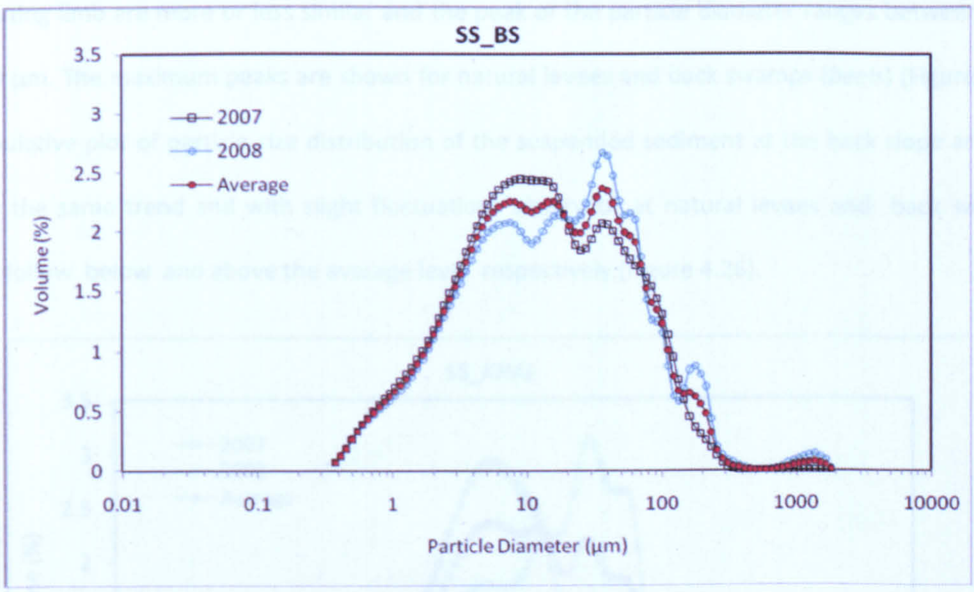


Figure 4.22 Particle size distribution of suspended sediment at back slope (SS_BS) of *Bara Bania Mauza of* Jamuna Floodplain in Bangladesh of 2007 and 2008 during flood

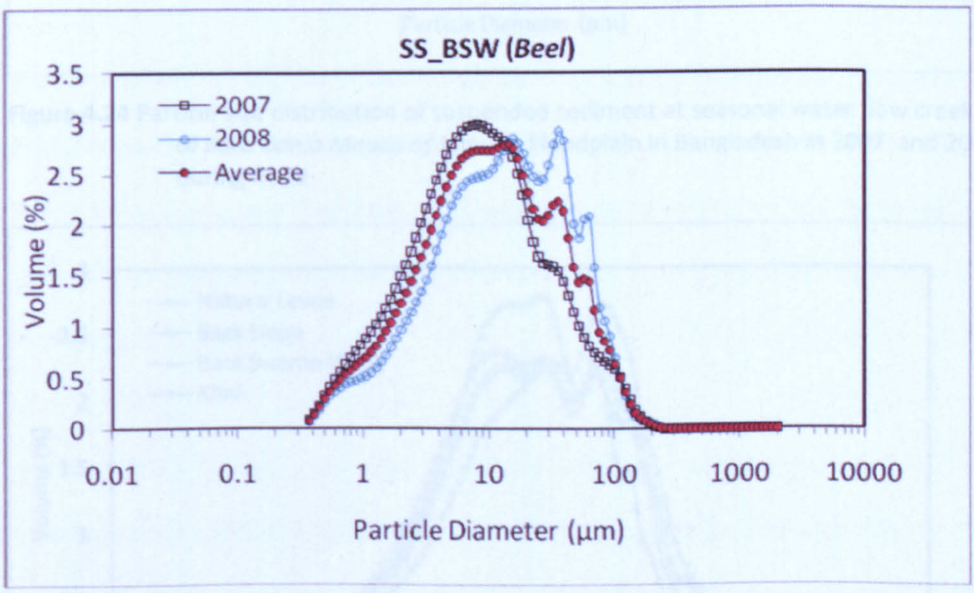


Figure 4.23 Particle size distribution of suspended sediment at Back Swamp of *Bara Bania Mauza of* Jamuna Floodplain in Bangladesh in 2007 and 2008 during flood

Comparing particle size among the four geomorphic units, the range of the increasing limb and decreasing limb are more or less similar and the peak of the particle diameter ranges between 4 µm to 100 µm. The maximum peaks are shown for natural levees and back swamps (*beels*) (Figure 4.25). A cumulative plot of particle size distribution of the suspended sediment at the back slope and *khal* follow the same trend and with slight fluctuations observed at natural levees and back swamps, which follow below and above the average level respectively (Figure 4.26).

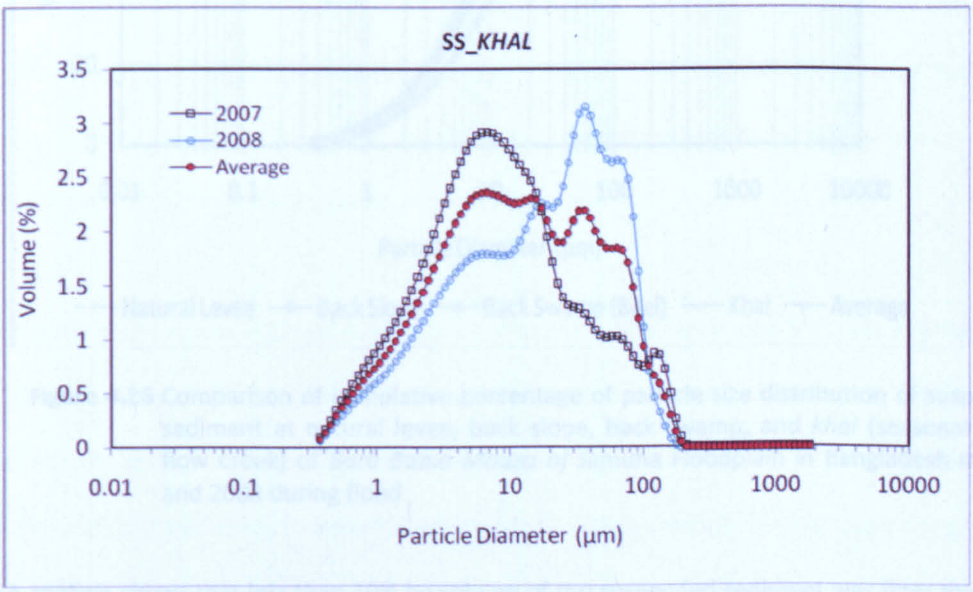


Figure 4.24 Particle size distribution of suspended sediment at seasonal water flow creek (*Khal*) of *Bara Bania Mauza of* Jamuna Floodplain in Bangladesh in 2007 and 2008 during flood

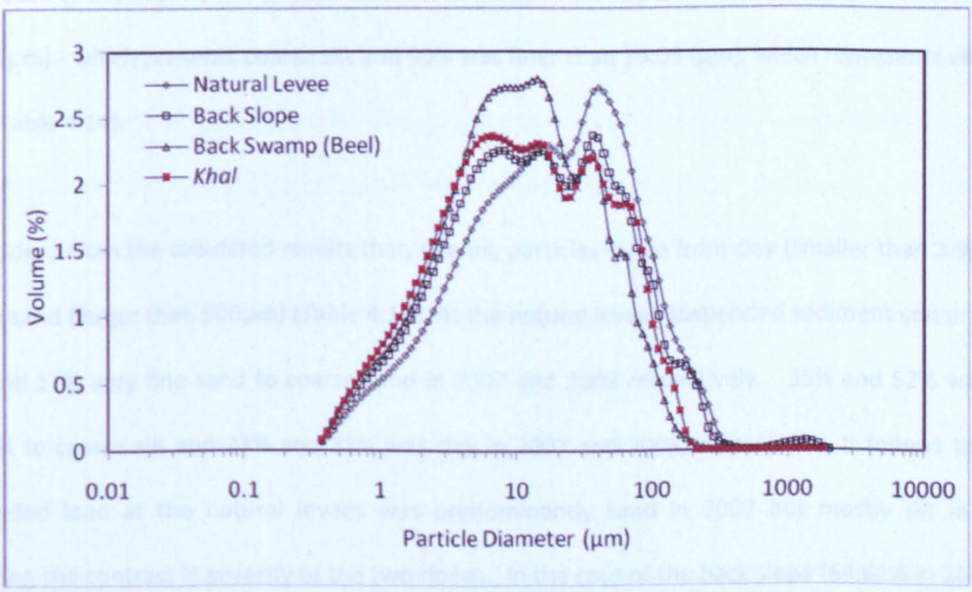


Figure 4.25 Comparison of particle size distribution of suspended sediment in the natural levee, back slope, back swamp, and *khal* (seasonal water flow creek) zones during the 2007 and 2008 floods (average).

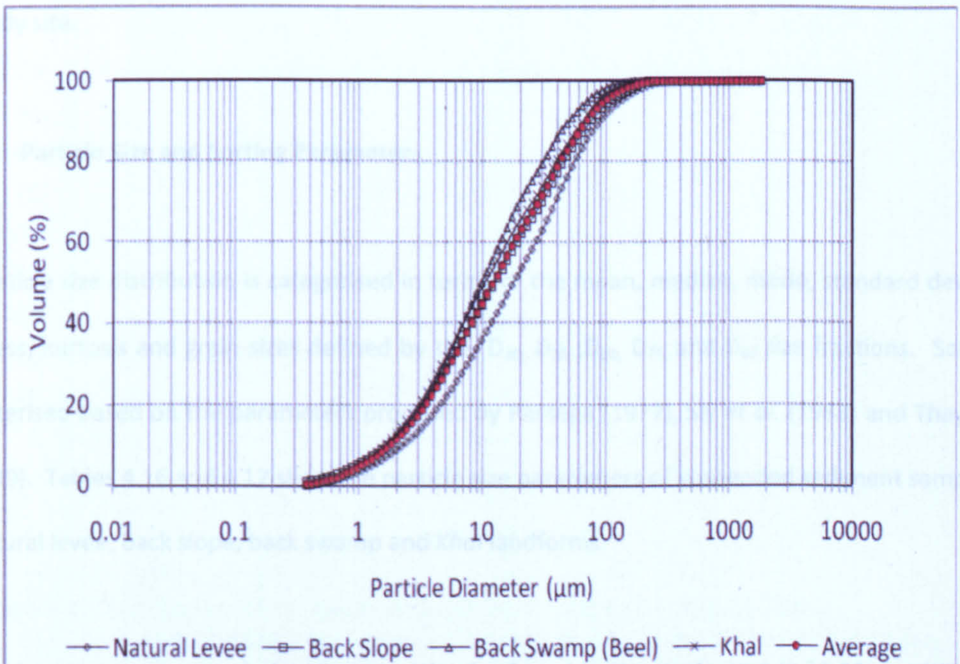


Figure 4.26 Comparison of cumulative percentage of particle size distribution of suspended sediment at natural levee, back slope, back swamp, and *khal* (seasonal water flow creek) of *Bara Bania Mauza of* Jamuna Floodplain in Bangladesh in 2007 and 2008 during flood

The PSA analysis shows that less than 10% by volume of the suspended sediment was finer than 2.49 (µm), which represents clay. Less than 25% was finer than 6.48 (µm), which represents very fine silt, about 50% of the sediment was finer than 16.82 (µm), which represents fine silt, 75% was finer than 37.21 (µm) - which presents coarse silt and 90% was finer than 76.03 (µm), which represents very fine sand (Table 4.14).

It is evident from the tabulated results that, overall, particles range from clay (smaller than 3.9µm) to coarse sand (larger than 500µm) (Table 4.15). At the natural levees suspended sediment comprised of 42% and 17% very fine sand to coarse sand in 2007 and 2008 respectively. 35% and 52% was very fine silt to coarse silt and 23% and 31% was clay in 2007 and 2008, respectively. It follows that the suspended load at the natural levees was predominantly sand in 2007 but mostly silt in 2008, reflecting the contrast in severity of the two floods. In the case of the back slope (64.62% in 2007 and 64.25% in 2008), back swamp (66.22% in 2007 and 73.93% in 2008) and *Khals* (61.30% in 2007 and

67.75% in 2008) show the same scenarios of silt-dominant suspended sediment concentrations over the study site.

4.5.6.3 Particle Size and Sorting Parameters

The particle size distribution is categorised in terms of the mean, median, mode, standard deviation, skewness, kurtosis and grain sizes defined by the D_{10}, D_{25}, D_{50}, D_{75}, and D_{90} size fractions.. Sorting is characterised based on the parameters proposed by Passega (1977), Sly *et al.* (1983) and Thayyen *et al.* (1999). Tables 4.16 and 4.17 show the particle size parameters of suspended sediment samples for the natural levee, back slope, back swamp and *Khal* landforms.

The maximum mean suspended sediment grain size found in the study area is 32.44µm at the back slope. The size of suspended sediment gradually decreases to the back swamps where it is 22.84µm. This means that the back swamps are characterised by finer particles than the levees, ridges and back slopes. The standard deviations of samples collected in the four geomorphic units reveal a wide range of sorting characteristics. The average value of skewness is 1.95µm showing particle size distributions are strongly skewed towards the fine particles, while the average kurtosis of 4.76µm (extremely leptokurtic) shows that the distributions are strongly peaked.

In addition, particle size fractions for the suspended sediment samples are presented on a CM diagram, where C represents D_{90} (the coarse sediment) and M is the D_{50} or median grain size, (Passega and Byramjee, 1969; Brown, 1985; Passmore *et al.,* 1992; Bravard and Peiry, 1999). The CM diagram depicts well-clustered distributions, and the pattern illustrates that the grain size is dominated by fine silt (Figure 4.27).

4.5.6.4 Spatial and temporal variations in sediment accumulation thickness

The results are summarized in Table 4.18 and illustrated in Figure 4.28. The ID's NLMB, BSMB and BSWMB stand for Natural Levee, Back Slope and Back Swamp Marker Bed. In 2007, the greatest

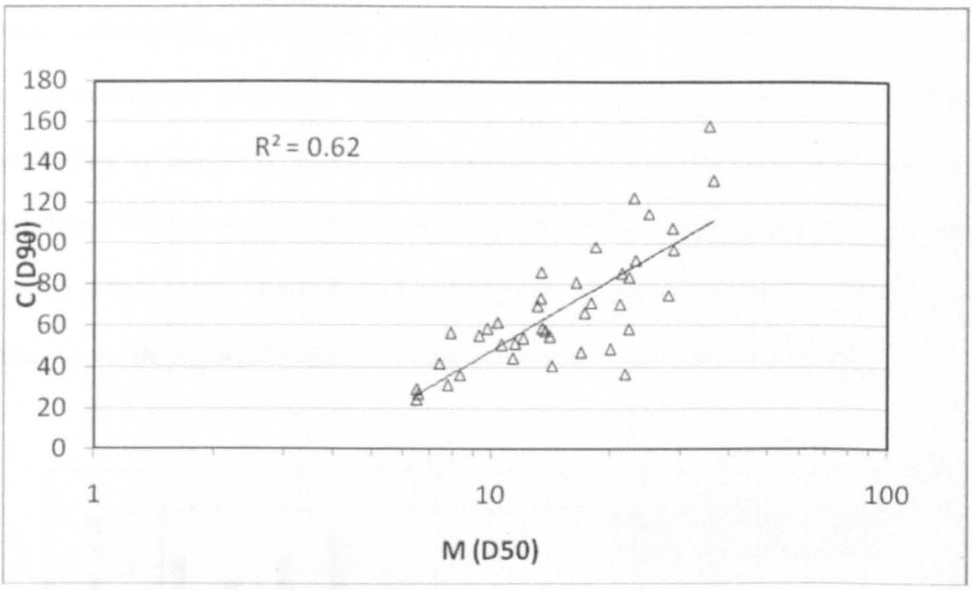


Figure 4.27 CM diagram to for suspended sediment sampled in the *Bara Bania Mauza*(village) of the Jamuna Floodplain during the 2007 and 2008 floods

thickness of sediment deposition (5.5cm) was observed on the natural levee, while the minimum (1.9cm) was observed in the back swamp (*beel)* zone. In 2008, the maximum (3.8cm) and minimum (0.5cm) deposition thicknesses were observed, in the same geomorphic units. Clearly, much more sediment accumulated in 2007 than 2008. In 2007, the average sediment deposition thickness recorded 5.02cm, 3.21cm and 2.0cm on the natural levee, back slope and back swamp areas (*beels*) respectrively. The equivalent figures in 2008 were 3.32cm, 1.88cm and 0.7cm on the same landforms. Taking all three landforms together, the average sediment deposition thickness 3.77cm and 2.29cm were in 2007 and 2008 accordingly.

This was the case because a large flood occurred in 2007, while the 2008 event was a normal flood, which is locally, known as a *Barsha*. It is generally perceived that when a *barsha* occurs, the flood hydraulics are predictable and the spatial distribution of sediment deposition pattern is much less variable then is the case during a large flood. The results also reveal that sediment accumulation thickness varies in a consistent and statistically significant manner with distance from the river in both years (Figure 4.29).

The rates of sediment accumulation measured in the present study were compared with data on floodplain sedimentation observed on other floodplains around the world (Table 4.19). This table allows comparison of inundation period and depth, suspended sediment concentration and deposition rate on natural levees and in floodplain areas more generally. Data from the Jamuna (1995), Rhine (1993), Meuse (1993) and Mississippi (1973) rivers were obtained from a flood action plan report (FAP24, 1996). These documents show the variation of the sedimentation patterns. It is found higher for the Jamuna floodplain, compared to other major river's floodplains.

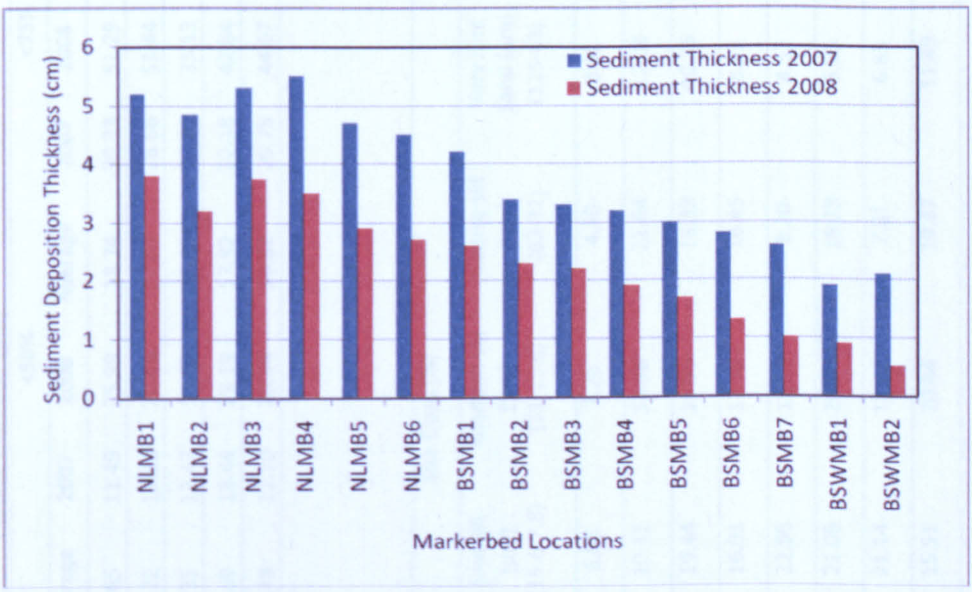


Figure 4.28 Variation of sediment deposition thickness of two different monsoons flood years

The spatial distribution of average sediment accumulation thickness of 2007 and 2008 is shown in Figure 4.30. This map was produced using the ArcGIS spatial analyst system to present the average sediment accumulation on the study area based on the 2007 and 2008 data. It shows the accumulation variation according to the landforms. The results suggest that at the natural levee area has the higher sediment deposition (4-6cm), followed by back slope (2-4cm) and back swamp (<2cm). It indicates that sediment deposition thickness varies with the landform distance to the river. Exploratory statistical techniques were also used to summarise the data (Table 4.20). Deposition thickness has been divided into three classes; 0-0.02m, 0.02-0.04m and 0.04-0.06m.

Table 4.14 Variation in the suspended sediment particle size distributions

Sampling Location	Particle Diameter (µm)														
	<10%			<25%			<50%			<75%			<90%		
	2007	**2008**	**Average**	**2007**	**2008**	**Average**	**2007**	**2008**	**Average**	**2007**	**2008**	**Average**	**2007**	**2008**	**Average**
Natural levee	1.94	4.12	3.03	4.57	10.74	7.65	11.49	25.99	18.74	30.33	51.29	40.81	64.12	96.50	80.31
Back slope	2.07	2.59	2.33	5.29	7.15	6.22	13.38	20.68	17.03	28.66	51.44	40.05	53.48	148.79	101.13
Back Swamp	1.93	2.38	2.15	4.84	5.87	5.35	12.47	14.92	13.69	27.82	33.13	30.48	51.25	60.71	55.98
Khal	2.09	2.84	2.46	5.33	8.06	6.69	13.44	22.19	17.82	32.18	42.84	37.51	64.71	68.70	66.71
Average	2.01	2.98	2.49	5.01	7.95	6.48	12.70	20.94	16.82	29.75	44.67	37.21	58.39	93.68	76.03

Table 4.15 Suspended sediment particle size classes

Sampling Location	Year	Size Class (%)								
		Clay (µm) <3.8	Very fine silt (µm) (7.8-3.9)	Fine silt (µm) (15.6-7.8)	Medium silt (µm) (31-15.6)	Coarse silt (µm) (63-31)	Very Fine Sand (µm) (125-63)	Fine sand (µm) (250-125)	Medium Sand (µm) (500-250)	Coarse sand (µm) >500
Natural Levee	2007	23.15	16.77	6.66	7.20	4.60	8.52	5.23	5.54	22.34
	2008	30.72	6.35	10.41	13.58	21.64	12.08	4.78	0.44	0.00
Back Slope	2007	22.64	15.90	19.44	15.95	13.33	10.36	2.27	0.10	0.00
	2008	21.02	14.00	16.01	17.79	16.45	8.93	4.55	0.36	0.88
Back Swamp *(Beel)*	2007	28.71	19.82	22.98	15.22	8.20	4.57	0.48	0.00	0.00
	2008	19.11	15.74	21.09	20.87	16.23	6.53	0.44	0.00	0.00
Khal (Seasonal water flow)	2007	30.27	19.87	21.14	12.68	7.61	6.83	1.61	0.00	0.00
	2008	20.47	12.33	15.51	20.04	19.87	11.49	0.30	0.00	0.00

Table 4.16 Suspended sediment particle size parameters

Sampling Locations	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Shorting Terms
Natural Levee	30.94	18.59	28.47	34.59	Widely sorted
Back slope	32.44	16.46	65.18	40.86	Widely sorted
Back swamp	22.84	13.57	18.65	25.59	Widely sorted
Khal	26.64	17.66	25.43	27.95	Widely sorted

Table 4.17 Distribution of suspended sediment particle sizes

Sampling Locations	Skewness (μm)	Kurtosis (μm)	D_{10} (μm)	D_{25} (μm)	D_{50} (μm)	D_{75} (μm)	D_{90} (μm)
Natural Levee	1.83	4.00	2.99	7.57	18.59	40.55	79.80
Back slope	2.04	5.15	2.30	6.12	16.46	37.57	95.17
Back swamp	2.01	4.94	2.19	5.39	13.57	30.38	57.75
Khal	1.93	4.94	2.45	6.65	17.66	36.97	64.90

Table 4.18 Sediment accumulation thicknesses measured at the marker beds in the study area of *Bara Bania Mauza* of Jamuna floodplain in Bangladesh

Marker bed _ID	X_Cordinate	Y_Cordinate	Sediment Deposition Thickness (cm)		Variation
			2007	2008	
NLMB1	479369	651616	5.2	3.8	-1.4
NLMB2	479853	651692	4.9	3.2	-1.7
NLMB3	479478	650230	5.3	3.8	-1.6
NLMB4	479812	649881	5.5	3.5	-2.0
NLMB5	479470	649966	4.7	2.9	-1.8
NLMB6	479787	649645	4.5	2.7	-1.8
BSMB1	480417	651469	4.2	2.6	-1.6
BSMB2	479678	650988	3.4	2.3	-1.1
BSMB3	479837	650513	3.3	2.2	-1.1
BSMB4	479585	649266	3.2	1.9	-1.3
BSMB5	479984	648905	3.0	1.7	-1.3
BSMB6	480021	648651	2.8	1.3	-1.5
BSMB7	480424	648312	2.6	1.0	-1.6
BSWMB1	480076	650414	1.9	0.9	-1.0
BSWMB2	479787	649274	2.1	0.5	-1.6

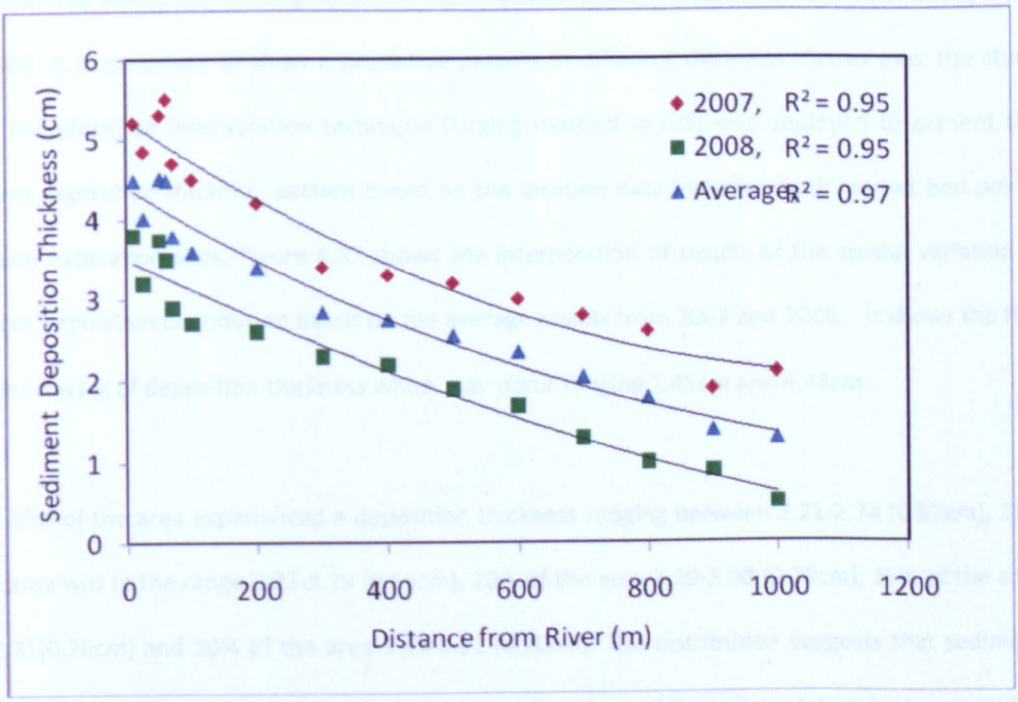


Figure 4.29 Variation of sediment deposition thickness with distance from river

Table 4.19 Comparison of observed sedimentation for different rivers with the results of the present study of *Bara Bania Mauza* of Jamuna floodplain in Bangladesh

River	Year of flood	Inundation		Suspended concentration	Deposition rates (m)	
		Period (days)	Depth (m)	(mg/l)	Levees	Floodplain
Rhine	1993	2-7	0.3-2	>150	-	0.002-0.01
Meuse	1993	3	0.6	400	0.03	0.002-0.01
Mississippi	1973	60	4	-	0.80-0.10	0.05-0.09
Jamuna	1995	40-99	2-2.8	500-600	0.20-0.30	0.001-0.004
Jamuna	2007	105	1-2.5	316	0.05	0.019
Jamuna	2008	75	0.5-1.5	273	0.038	0.005

Sources: Asselman and Middelkoop (1995), FAP24 (1996) and present study

In total about 23% of the study area exhibited the highest deposition thickness of 0.04-0.06m, while the equivalent figures were 68% for the 0.02-0.04m band and 9% for the 0-0.02m band (Figure 4.31). The standard deviations for the highest and lowest sediment thickness are the same and are less than half the value for the middle (0.02-0.04m) category of deposition.

As, figure 4.30 shows the existing sediment accumulation pattern is based on the field survey 2007 and 2008. It is necessary to show a predictive pattern in different thickness classes over the study area. Therefore, an interpolation technique (kirging method in GIS) was deployed to present the sediment deposition thickness pattern based on the location data including both marker bed points and open excavation sites. Figure 4.32 shows the interpolation of results of the spatial variation in sediment deposition distribution based on the average results from 2007 and 2008. It shows the five different classes of deposition thickness which may occur ranging 1.45cm and 4.44cm.

About 30% of the area experienced a deposition thickness ranging between 2.21-2.74 (0.53cm), 25% of the area was in the range 2.73-3.29 (0.56cm), 20% of the area 3.29-3.90 (0.79cm), 15% of the area 1.45-2.21(0.76cm) and 10% of the area 1.45-2.21 (0.76cm). The distribution suggests that sediment accumulation is greatest close to the main river and the *khals* while sedimentation is slower on the back slope and in the back swamp (*beel*) areas.

Table 4.20 Sediment deposition thicknesses (average of 2007 and 2008 floods year).

Sediment thickness(m)	Total area (hectares)	Standard Deviation	Variance	Percentage
0-0.02	116	0.28	0.04	9
0.02-0.04	296	0.54	0.15	23
0.04-0.06	877	0.28	0.08	68

4.5.6.5 Particle size distributions of accumulated sediments

The particle size distributions established in this study are shown in Figures 4.33 to 4.36. The results revealed a consistent trend for the fine sediment below zero (ϕ), which is an intuitive representation of the percentage of sediment volume. The resulting graphs also describe the volume of sediment particles distribution among the various particle sizes.

The descriptive statistics reveal that the sediment of natural levee, back slope and back swamps, which consists of a median particle size classified as medium sand with a distinct pattern of skewness.

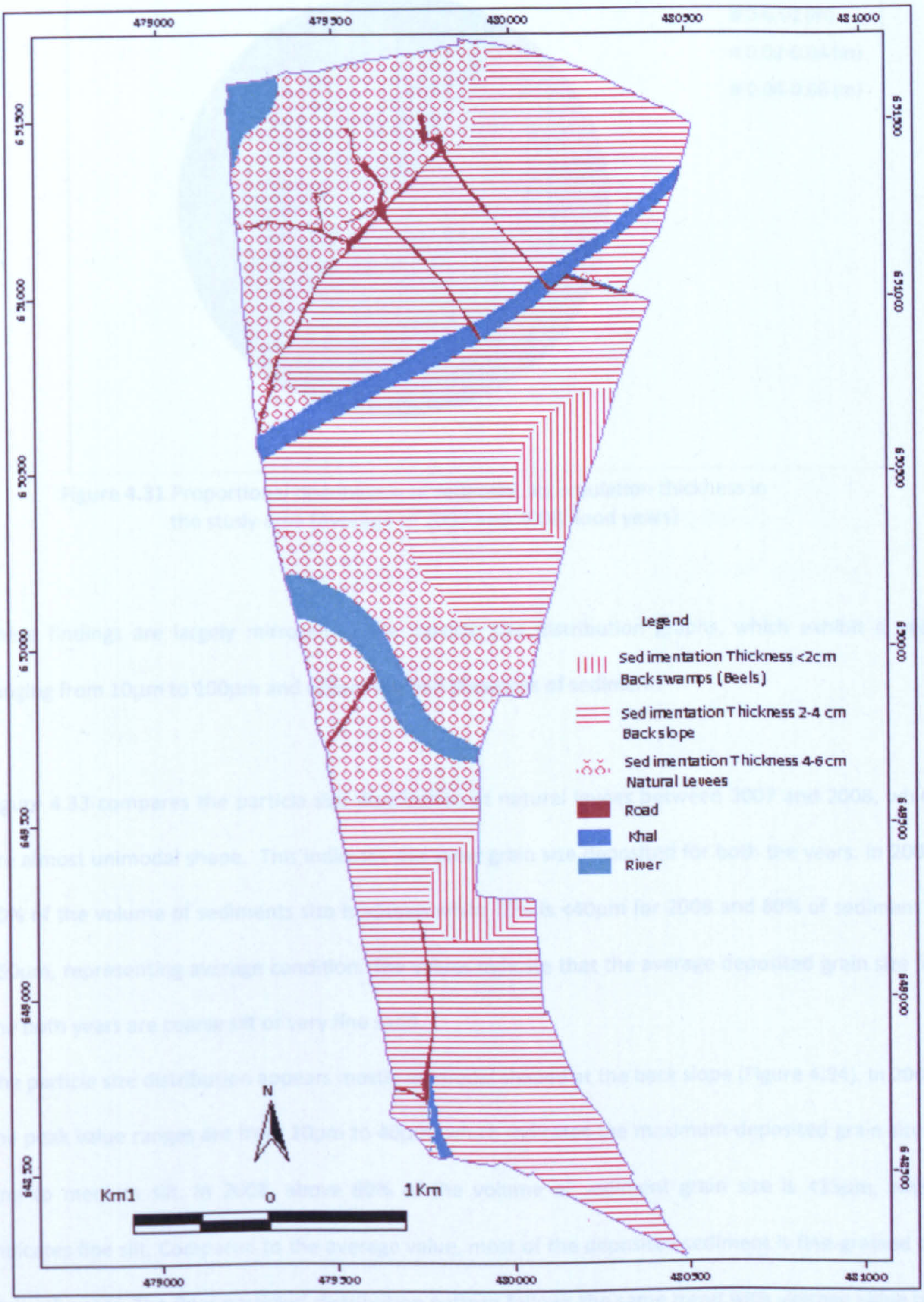


Figure 4.30 Spatial distribution of sediment thickness in the study area using average record of 2007 and 2008

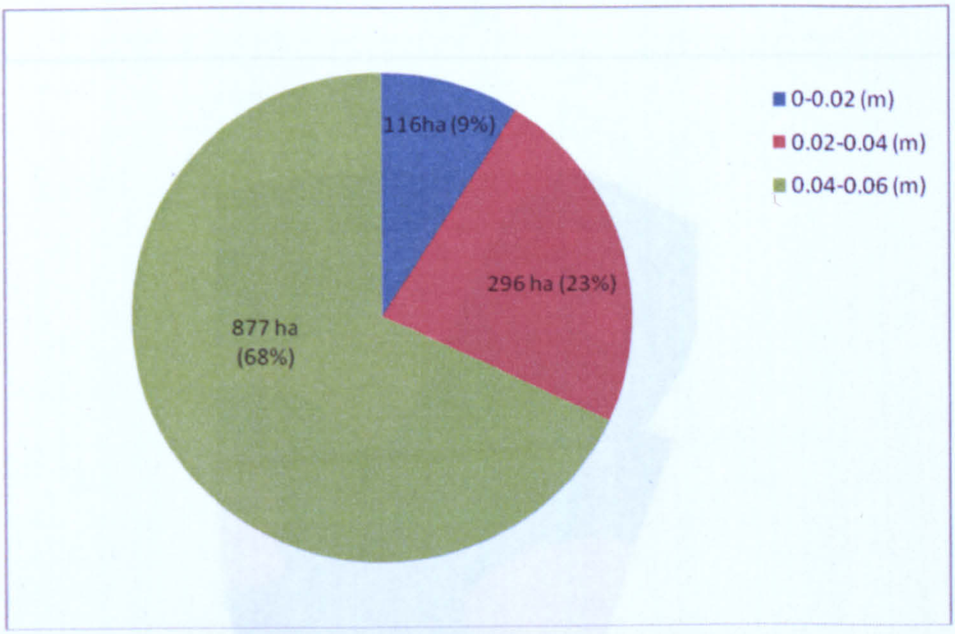


Figure 4.31 Proportional distribution of sediment accumulation thickness in the study area (Average of 2007 and 2008 flood years)

These findings are largely mirrored in the particle size distribution graphs, which exhibit a peak ranging from 10μm to 100μm and reflect the fine skewness of sediment.

Figure 4.33 compares the particle size distribution at natural levees between 2007 and 2008, which are almost unimodal shape. This indicates the same grain size deposited for both the years. In 2007, 90% of the volume of sediments size is <50μm while 75% is <40μm for 2008 and 80% of sediment is <50μm, representing average condition. The values indicate that the average deposited grain size for the both years are coarse silt or very fine sand.

The particle size distribution appears mostly unimodal shaped at the back slope (Figure 4.34). In 2007, the peak value ranges are from 10μm to 40μm, which indicates the maximum-deposited grain size is fine to medium silt. In 2008, above 80% of the volume of sediment grain size is <15μm, which indicates fine silt. Compared to the average value, most of the deposited sediment is fine-grained silt for both years. The finer particles' distribution pattern follows the same trend with average value but in the case of coarser particle distribution, the pattern is different. In 2007, the volume of coarse particles deposition is more compared to 2008. This happened because in 2007 a high flood occurred, while 2008 experienced a normal flood.

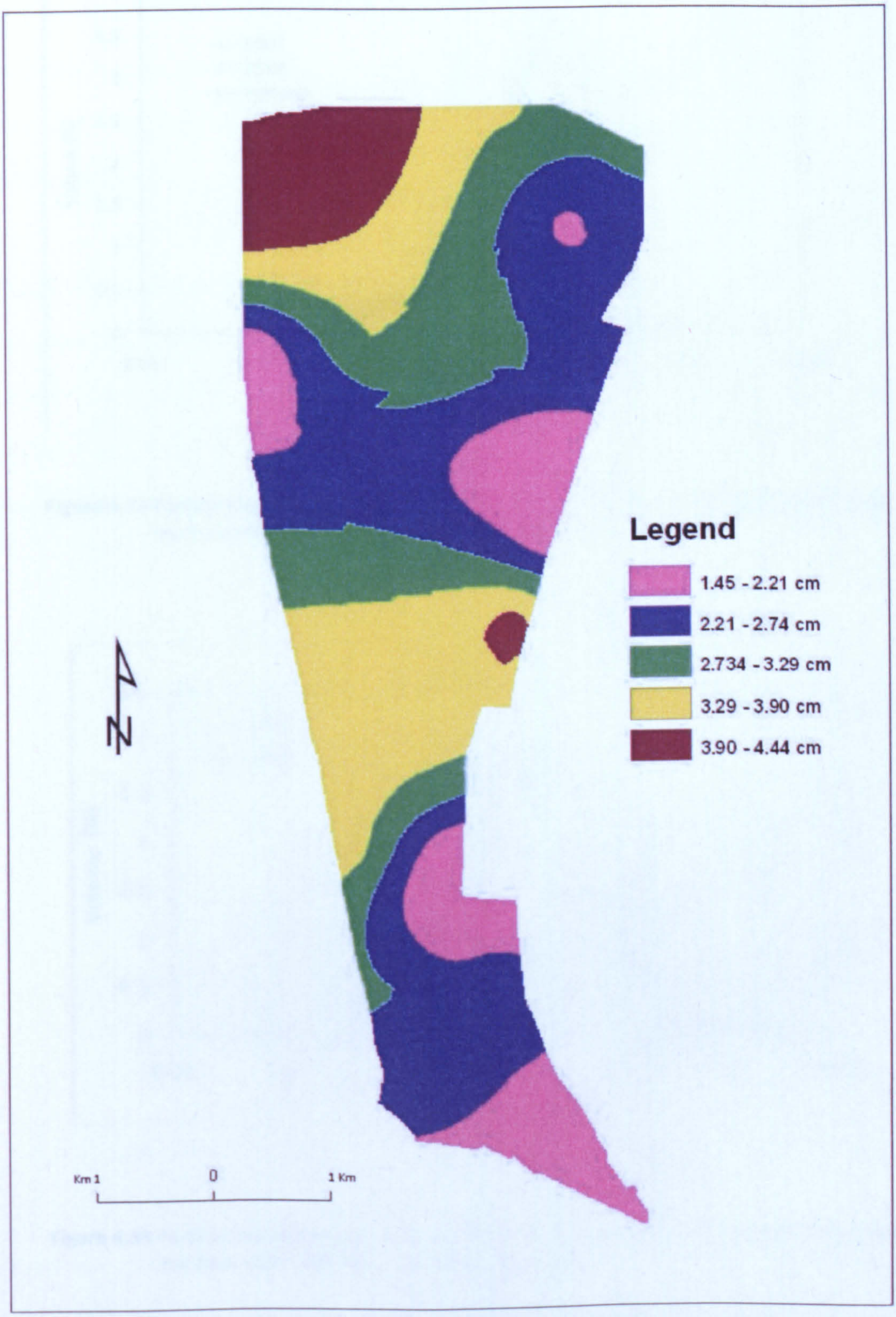


Figure 4.32 Interpolation of sediment accumulation thickness over the study area for 2007 and 2008

[Note: Interpolation performed using geo-statistical analysis; kriging, semivariogram spherical model, natural breaks (Jenks) classification techniques]

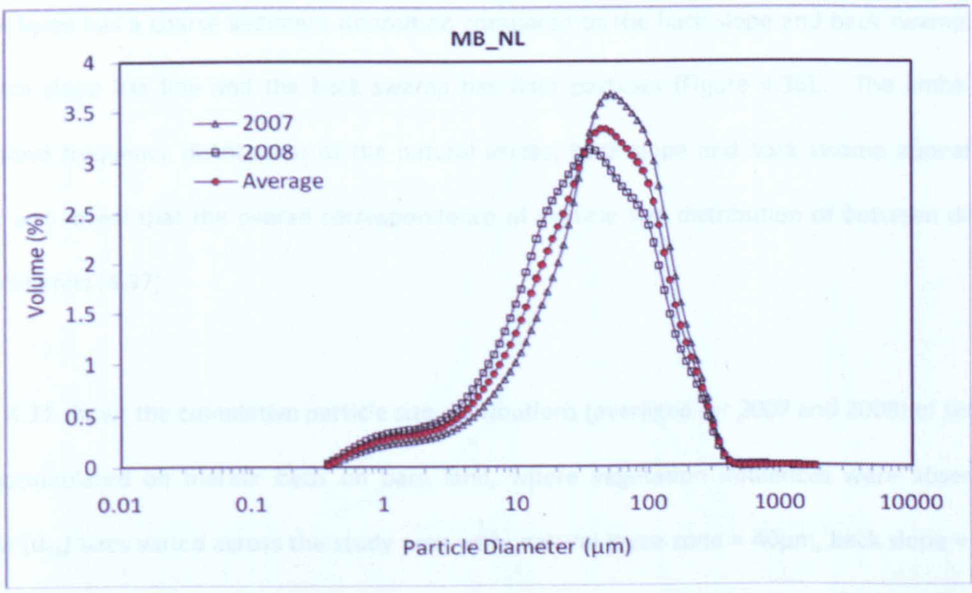


Figure 4.33 Particle size distributions for sediment that accumulated on marker beds located on the natural levee (MB_NL) in 2007 and 2008

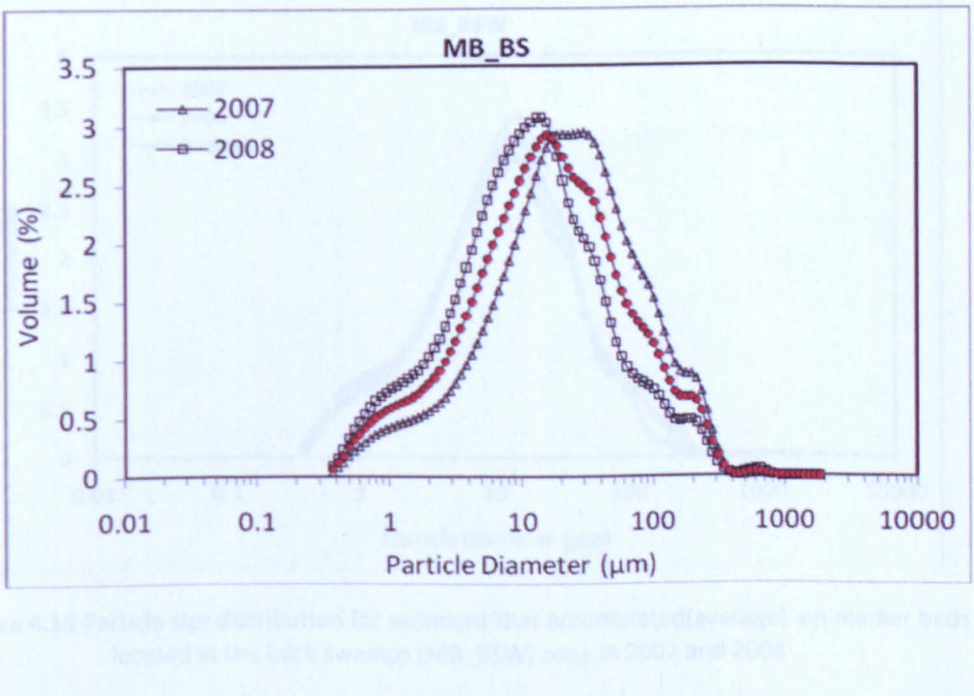


Figure 4.34 Particle size distribution for sediment that accumulated on marker beds located in the back slope (MB_BS) zone in 2007 and 2008

The particle size distributions for back swamps (*beels)* show the same trend and appear as unimodal for both years (Figure 4.35). The average grain size of the peak is 10µm (fine silt) for both cases. The natural levee has a coarse sediment deposition compared to the back slope and back swamp (*beel*). The back slope has fine and the back swamp has finer particles (Figure 4.36). The limbs of the cumulative frequency distribution of the natural levees, back slope and back swamp appear to be similar and reveal that the overall correspondence of particle size distribution of between different landform units (4.37).

Figure 4.37 shows the cumulative particle size distributions (averaged for 2007 and 2008) of sediment that accumulated on marker beds on bare land, where vegetation influences were absent. The median (d_{50}) sizes varied across the study area with: natural levee zone = 40μm, back slope = 15μm, and back swamp = 11μm. The corresponding d_{90} values were: natural levee = 105μm, back slope = 80μm and back swamp = 50μm.

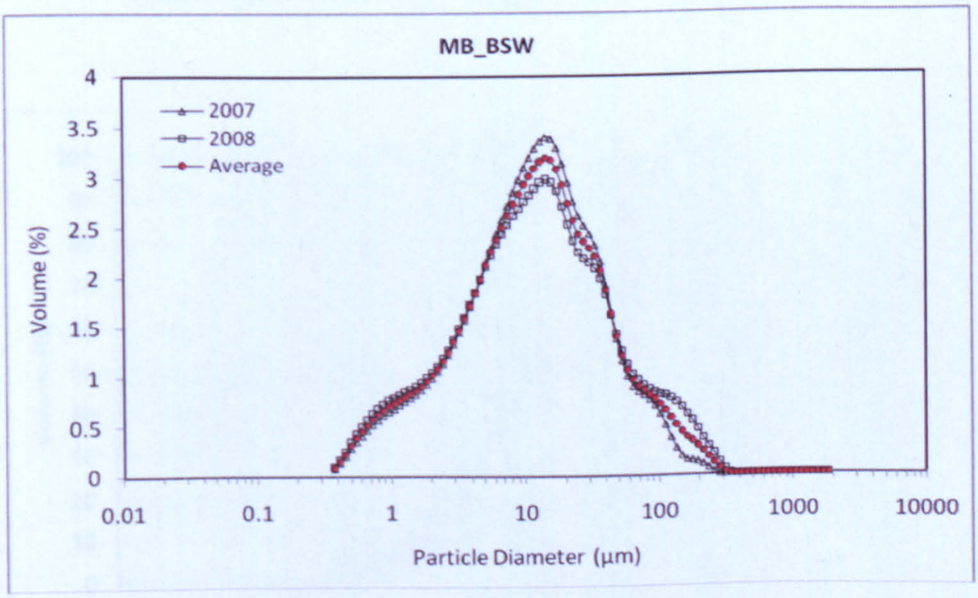


Figure 4.35 Particle size distribution for sediment that accumulated(average) on marker beds located in the back swamps (MB_BSW) zone in 2007 and 2008

The sediment that accumulated within the crops growing in agricultural fields was, on average, coarser than that measured on bare land (see Chapter 4). For example, an average d_{90} = 260μm (medium sand) was recorded for cropped fields in the natural levee zone in the post-monsoon season of 2007. The equivalent figure in 2008 was 180μm (fine sand).

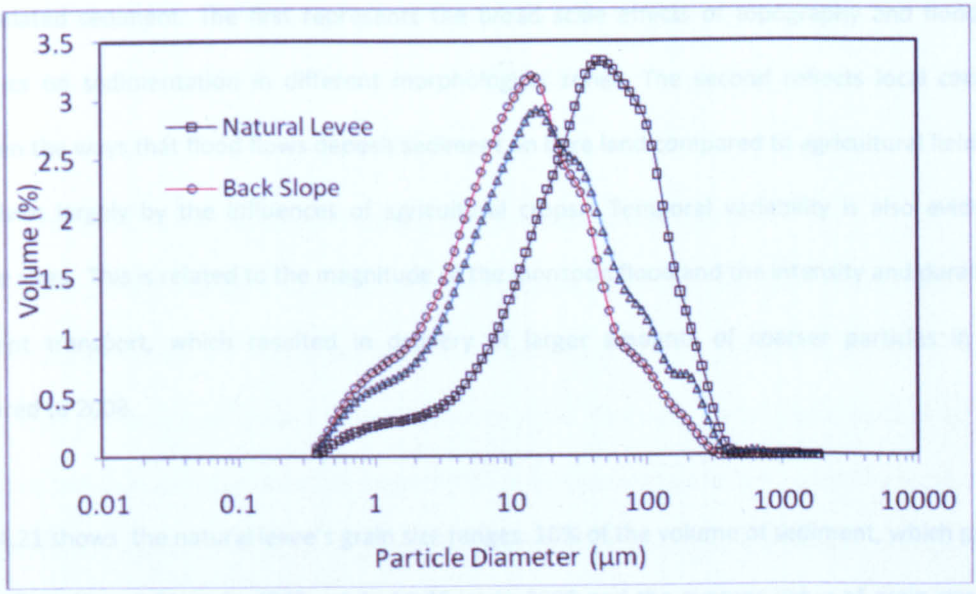


Figure 4.36 Comparison of particle size distribution for sediments that accumulated on marker beds in the natural levee, back slope and back swamp (*Beel)* zones of the *Bara Bania Mauza* in 2007 and 2008 (average).

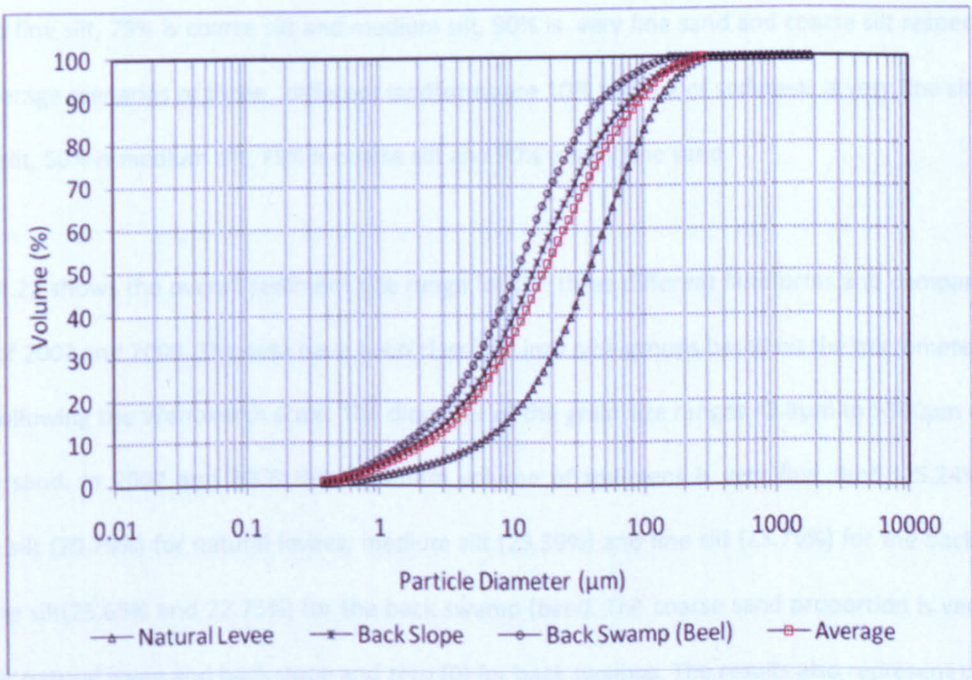


Figure 4.37 Comparison of cumulative particle size distributions for sediments that accumulated on marker beds in the natural levee, back slope and back swamp (*Beel)* zones of the *Bara Bania Mauza* in 2007 and 2008.

These findings illustrate two scales of spatial variability in the particle size distributions of accumulated sediment. The first represents the broad scale effects of topography and flood flow dynamics on sedimentation in different morphological zones. The second reflects local contrasts between the ways that flood flows deposit sediment on bare land compared to agricultural fields that are driven largely by the influences of agricultural crops. Temporal variability is also evident in particle sizes. This is related to the magnitude of the monsoon flood and the intensity and duration of sediment transport, which resulted in delivery of larger amounts of coarser particles in 2007 compared to 2008.

Table 4.21 shows the natural levee's grain size ranges. 10% of the volume of sediment, which particle size is finer than 6.61μm in 2007, while 10.25μm in 2008 and the average value of grain size of is 8.43μm. This indicates that only 10 % of the volume of sediment is fine silt. Thus, 25% is medium silt and 50% is coarse silt, 75% is very fine sand and 90% is fine sand. Similarly, 10% of the volume of sediment is clay for the back slope and back swamp, 25% is fine silt and very fine silt, 50% is medium silt and fine silt, 75% is coarse silt and medium silt, 90% is very fine sand and coarse silt respectively. The average scenarios of three different landforms are 10% volume of sediment is very fine silt, 25% is fine silt, 50% is medium silt, 75% is coarse silt and 90% is very fine sand.

Table 4.22 shows the overall sediment size range for the three different landforms and compares the years of 2007 and 2008. The data have been classified into nine groups based on the micrometer (μm) scale following the Wentworth scale. The diameter of the grain size ranges <3.8μm to >500μm clay to coarse sand. In 2007 and 2008 the maximum volume of sediment is very fine sand (25.24%) and coarse silt (20.79%) for natural levees, medium silt (23.39%) and fine silt (23.79%) for the back slope and fine silt(25.65% and 22.75%) for the back swamp (*beel)*. The coarse sand proportion is very low, <1% for natural levee and back slope and zero (0) for back swamps. The results also represent particle size ranges from very fine silt to very fine sand account for approximately 90% of the total deposited sediment.

In particular, medium silt, coarse silt and very fine sand are the dominant sizes for natural levees in 2007 and 2008. At the back slope, it varies with fine silt, medium silt and coarse silt in 2007 and very fine silt, fine silt and medium silt in 2008. There appears to be a minor variation within the fine silt particles between the two monsoon years. At back swamps (*beel*), the dominant grain sizes range from clay up to medium silt for both the years of 2007 and 2008.

4.5.6.6 Particle Size Parameters and Sorting of accumulated sediments

The resulting particle size parameters for the natural levee, back slope and back swamp (*beel*) zones of the floodplain in the study area are listed in Tables 4.23 and 4.24. The size of the material in an alluvial river environment always varies with the flood hydraulics. The mean particle sizes for deposited sediment samples show the longitudinal and lateral size variations. Works by Bluck (1982), Ashmore (1982), Ashworth *et al.*, (1992) and Islam (2006) have attributed the particle size variation of different bar sedimentation along the longitudinal, lateral and vertical aspects. Their research focuses on the grain size pattern at different locations and the trend is upward fining of deposited sediment in the channel depositional environment. A similar pattern has been observed in the overbank floodplain sedimentation in a longitudinal and lateral direction. The mean, median and mode measure the central tendency of the size distribution. Comparing the years 2007 and 2008, the maximum mean grain size measured 45.31μm, 43.76μm for the natural levee, 45.66μm and 38.11μm for the back slope and 22.09μm, 26.58μm for the back swamp (*beel*). Results reveal that coarser grain deposited in 2007 and finer grained in 2008 for natural levees and back slope with a minor exception for back swamps. However, this relatively small amount of difference might be simply related to micro-scale local natural variability. The standard deviations of the three different geomorphic units reveal the degree of scatter, uniformity and homogeneity of sediment particles. The values of the standard deviations represent the range of sorting characteristics and transportation speeds during the sedimentation. The median size for sediment accumulating on the natural levee in 2007 (43.8μm) is in the coarse silt size class while in 2008 the median size was medium silt (31.2μm). However, the coarse grain silt 51.61μm and 37.03μm have been observed in accumulation for the both years. Overall, the sediment that accumulated on the levee was well sorted, reflecting uniformity in the overbank flow velocities and depths in this landform zone.

In the back slope zone, median sizes of 26.1μm and 21.4μm indicate medium silt in both 2007 and 2008. Here also, a higher volume of coarse grain silt (38.12μm) was deposited in 2007 and medium silt (29.67μm) in 2008. The grain size distribution of the accumulated sediments show well sorted on the natural levee. The median values for the back swamps (*beels*) were, 13.1μm and 13.7μm in 2007 and 2008, respectively, revealing fine silt deposition in both years. Field evidence reveals that the spatial variation of the grain size has occurred due to the local and small scale landform variability and in addition the two different flood magnitudes. But, the sediment grain size distribution have found 'well sorted' with relative fluctuations that has occurred due to variability of transportation speeds, vegetation cover and landforms characteristics for both years.

The degree of symmetry and the assessment of dominance for particular sediment fractions was measured by skewness and kurtosis. The positive skewness in the size distributions for all landform zones indicates that accumulated sediments are strongly skewed towards fine particles in both years. The kurtosis values show that the particle size distributions for all landform's zones are extremely leptokurtic (peaked). Examining the size fractions listed in Table 4.24 reveals that D_{10} ranges from clay to fine silt, D_{25} is very fine to medium silt, D_{50} is fine silt to coarse silt, D_{75} is medium silt to fine sand, and D_{90} is coarse silt to fine sand.

4.5.6.7 Precision Assessment

It is important in any statistical treatment of samples collected in the field to assess the accuracy and reliability of the results (Petrie and Diplas, 2000; Islam, 2006). In this respect, McCave and Syvitski (1991) described the difficulty of specifying the accuracy of any parameter of particle size distribution due to natural variability and operator impacts on the sample collection and processing techniques (Lieberman, 1996). Early studies used sieving and pipette methods to determine particle size distributions. These techniques are time consuming and difficult to measure more precisely (Livingstone *et al.,* 1999). In contrast, Lieberman (1996) identified the advantages of hi-technology methods like laser particle sizing in measuring particle sizes and characterising the size distribution. Laser instruments provides PSA information more precisely and without any manual involvement (Konert and Vandenberghe, 1997; Livingstone *et al.,* 1999).

Table 4.21 Comparison of particle size distributions for sediments that accumulated on marker beds in the study area of *Bara Bania mauza* in 2007 and 2008

	Particle Diameter (µm)														
Sampling Location	**<10%**			**<25%**			**<50%**			**<75%**			**<90%**		
	2007	**2008**	**Average**	**2007**	**2008**	**Average**	**2007**	**2008**	**Average**	**2007**	**2008**	**Average**	**2007**	**2008**	**Average**
Natural levee	6.61	10.25	8.43	16.66	26.05	21.35	32.96	51.33	42.14	57.81	92.37	75.09	99.39	156.25	127.82
Back slope	3.11	3.99	3.55	8.42	11.16	9.79	20.73	27.95	24.34	47.41	63.93	55.67	87.61	117.22	102.42
Back Swamp	1.82	2.09	1.96	5.14	5.46	5.30	13.17	12.73	12.95	31.03	26.52	28.77	70.61	50.98	60.79
Average	3.85	5.44	4.65	10.07	14.22	12.15	22.29	30.67	26.48	45.41	60.94	53.18	85.87	108.15	97.01

Table 4.22 Sediment size classes for different landform zones in 2007 and 2008

		Size Class (%)								
Sampling Location	Year	Clay (µm) <3.8	Very fine silt (µm) (7.8-3.9)	Fine silt (µm) (15.6-7.8)	Medium silt (µm) (31-15.6)	Coarse silt (µm) (63-31)	Very Fine Sand (µm) (125-63)	Fine sand (µm) (250-125)	Medium Sand (µm) (500-250)	Coarse sand (µm) >500
Natural Levee	2007	5.69	4.19	9.48	18.69	24.98	25.24	10.07	1.59	0.08
	2008	8.38	6.43	14.69	22.61	20.79	18.63	7.21	1.14	0.12
Back Slope	2007	11.99	9.60	18.80	23.39	17.14	12.32	5.76	0.83	0.16
	2008	21.80	16.46	23.79	18.85	9.46	5.87	3.06	0.49	0.23
Back Swamp *(Beel)*	2007	20.26	16.08	25.65	22.13	10.18	4.90	0.81	0.01	0.00
	2008	22.15	15.50	22.75	19.22	10.29	6.74	3.18	0.18	0.00

Table 4.23 Comparison of sediment size parameters for accumulated sediments

Sampling Location	Year	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Shorting Terms
Natural Levee	2007	45.31	43.76	51.61	66.57	Well sorted
	2008	43.76	31.24	37.03	52.98	Well sorted
Back Slope	2007	45.66	26.07	38.12	57.75	Well sorted
	2008	38.11	21.42	29.67	50.03	Well sorted
Back Swamp *(Beel)*	2007	22.09	13.13	15.66	28.37	Well sorted
	2008	26.58	13.67	16.22	38.13	Well sorted

Table 4.24 Comparison of sediment size parameters for accumulated sediments

Sampling Location	Year	Skewness (μm)	Kurtosis (μm)	D_{10} (μm)	D_{25} (μm)	D_{50} (μm)	D_{75} (μm)	D_{90} (μm)
Natural Levee	2007	2.88	15.93	8.52	21.68	43.76	82.03	138.13
	2008	3.55	20.36	6.34	15.62	31.24	55.63	94.42
Back Slope	2007	2.76	11.64	3.91	10.79	26.07	57.70	110.26
	2008	3.01	12.16	3.27	8.89	21.42	47.28	89.48
Back Swamp *(Beel)*	2007	2.90	12.02	2.16	5.69	13.13	26.64	50.00
	2008	3.28	13.05	2.03	5.61	13.67	29.97	63.73

Laser particle size analysis is now the most widely used technique and the quality of computer-based software is constantly improving (Bott and Hart, 1996; Konert and Vandenberghe, 1997).

The present study employed the most recent version of the Coulter LS™ Laser Diffraction Particle Size Analyser (LDPSA), which transmits sediment size parameters directly to a computer and displays the results automatically. This method depends on analysing the diffraction pattern produced when particles of different sizes are exposed to a collimated beam of light. It provides descriptive statistics based on the volume of sediments in a sample that are useful for further analysis (Bott and Hart, 1996).

To check the accuracy and reliability of the particle size analyses conducted in this study, 10% of the samples (8 out of 80), covering three different landforms, were selected, randomly, for reanalysis. The size distribution parameters of the reanalysed samples were then compared with the results for primary samples to establish the repeatability of the analyses (Table 4.25).

Table 4.25 Precision and reliability of the PSA

Sample No. and ID	Sample Status	Sediment Parameters (µm)					
		Mean	Mean	Mean	Mean	Mean	Mean
Natural levee-1 (NL MB 1)	Primary sample	45.31	43.76	51.61	66.57	43.76	138.13
	Reanalysed sample	43.56	43.50	51.20	65.17	43.50	137.13
	Differences (%)	3.86	0.59	0.79	2.10	0.59	0.72
Natural levee-2 (NL MB 2)	Primary sample	47.31	49.76	55.61	65.57	49.76	142.13
	Reanalysed sample	46.39	48.97	52.56	66.25	48.97	139.43
	Differences (%)	1.94	1.59	5.48	1.03	1.59	1.90
Natural levee-3 (NL MB 3)	Primary sample	44.40	47.17	55.36	66.15	447.17	145.13
	Reanalysed sample	43.74	46.54	54.63	65.21	46.54	144.45
	Differences (%)	1.49	1.34	1.32	1.42	1.34	0.47
Back slope-1 (BS MB 1)	Primary sample	44.66	27.07	37.12	55.75	27.07	112.26
	Reanalysed sample	43.26	25.10	35.22	54.65	25.10	111.22
	Differences (%)	3.13	7.28	5.19	1.97	7.28	0.93
Back slope-2 (BS MB 2)	Primary sample	44.26	26.10	36.42	55.35	26.10	110.52
	Reanalysed sample	44.10	26.03	35.43	55.25	26.03	109.65
	Differences (%)	0.36	0.27	0.99	0.18	0.27	0.79
Back slope-3 (BS MB 3)	Primary sample	42.10	25.03	33.43	54.25	25.03	108.65
	Reanalysed sample	41.90	24.80	32.40	53.85	24.80	107.70
	Differences (%)	0.48	0.92	3.08	0.74	0.92	0.87
Back Swamp-1 (BSW MB 1)	Primary sample	21.09	14.13	16.66	28.37	14.13	51.01
	Reanalysed sample	20.90	13.85	15.96	27.77	13.85	50.40
	Differences (%)	0.90	1.98	4.20	2.11	1.98	1.20
Back Swamp-2 (BSW MB 2)	Primary sample	26.58	13.67	16.42	37.13	13.67	62.73
	Reanalysed sample	25.90	12.99	15.98	36.87	12.99	61.90
	Differences (%)	2.56	4.97	2.68	0.70	4.97	1.32

Comparison of the primary and reanalysed sediment parameters demonstrates a very good level of analytical precision in the sediment size analyses for the samples. Differences between primary and reanalysed parameters are less than 1% for about 90% of the samples. Differences for the remaining 10% of reanalysed samples are in the range 2 to 7%. It may be concluded that the LS coulter counter method for particle size analysis used in this study has measured particle sizes accurately and provided detailed statistics reliably.

4.5.7 Comparison of the grain size composition of suspended and deposited sediment

Comparisons of the particle grain sizes between suspended and deposited sediment are shown in figure 4.38, 4.39 and 4.40. The results suggest significant differences in the grain sizes of suspended and deposited sediment at the different landforms in 2007 and 2008. In the natural levee zone, 50% of the particle grain sizes are finer than 10μm (fine silt) of suspended sediment, while deposited sediment grain sizes are finer than 35μm (coarse silt) in 2007. In 2008, it is found finer than 12μm (fine silt) of suspended sediment grain size and 25μm (medium silt) of deposited sediment grain sizes at the same landform (Figure 4.38).

It reveals that in both years, suspended sediment grain sizes were finer than the deposited sediment. In the back slope zone, 50% of the particle grain sizes were finer than 15μm (fine silt) of suspended sediment and 40μm (coarse silt) of deposited sediment in 2007, while the figures were 9μm (fine silt) and 18μm (medium silt) respectively in 2008 (Figure4.39). These results also suggest that particle grain sizes of suspended sediment were finer than the deposited sediment at the back slope area in both years.

The particle grain sizes of the suspended and deposited sediment in the back swamp zone varied little in 2007 and 2008. The results suggest that 50% of the particle grain sizes were finer than 10μm (fine silt) of suspended sediment and 12μm (fine silt) of deposited sediment in 2007, while 13μm (fine silt) and 14μm respectively were found in 2008. These results show that particle grain sizes vary from 10μm to <20μm for the both suspended and deposited sediment and the same trend was apparent in both 2007 and 2008 (Figure 4.40). These results also suggests that finer grained sediment usually accumulates far away from the river.

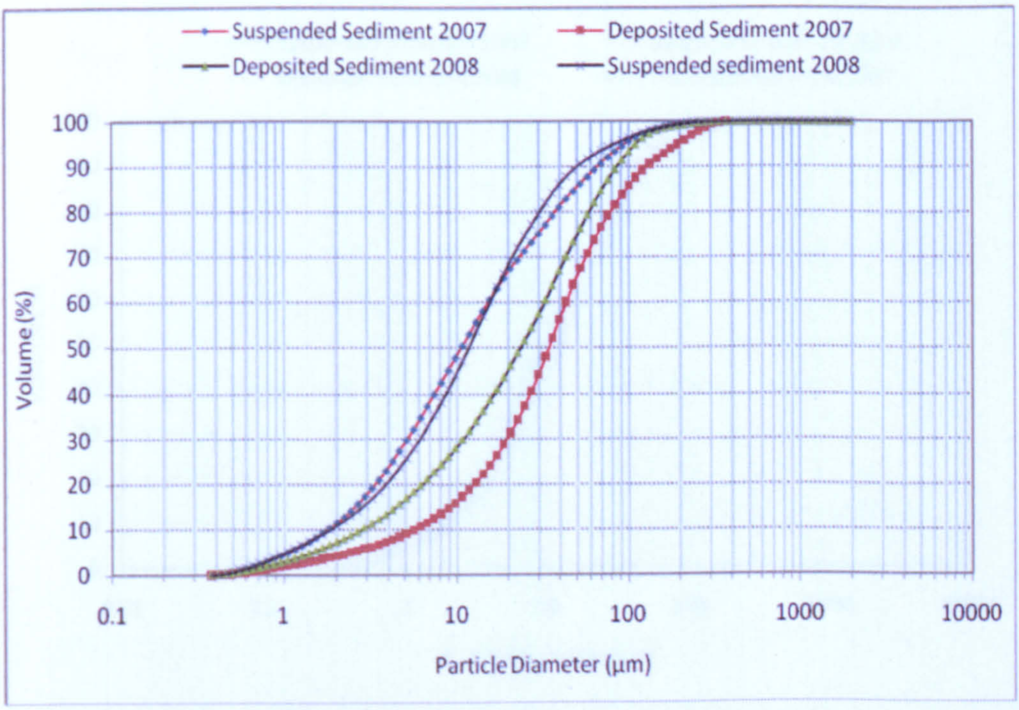


Figure 4.38 Comparison of the grain size composition of suspended and deposited sediment at the natural levee in 2007 and 2008

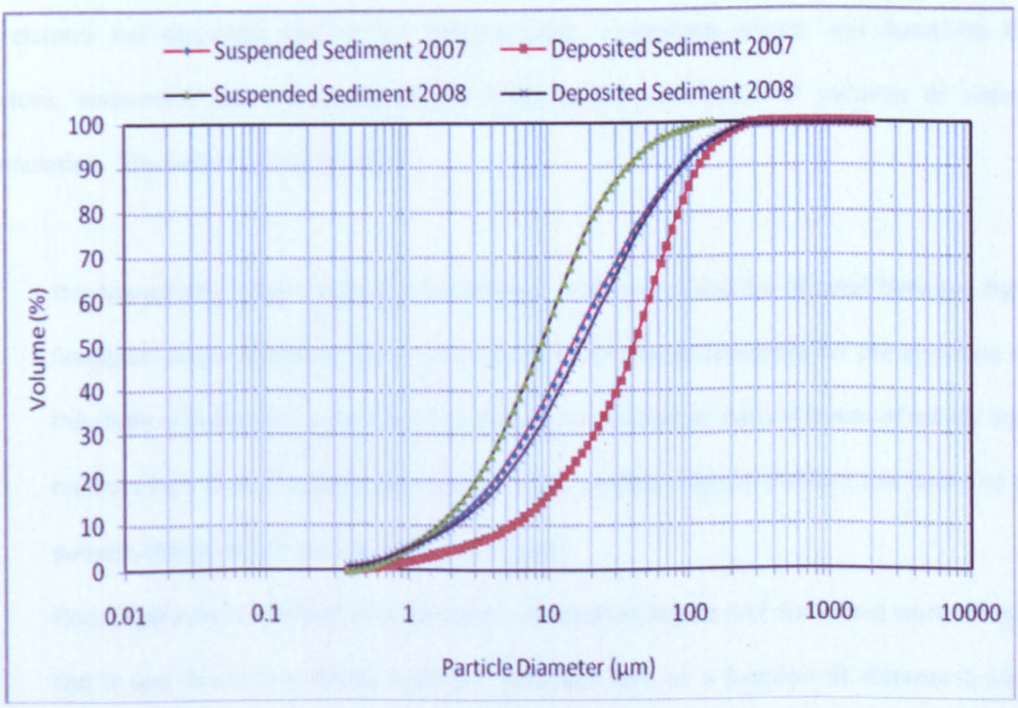


Figure 4.39 Comparison of the grain size composition of suspended and deposited sediment at the back slope in 2007 and 2008

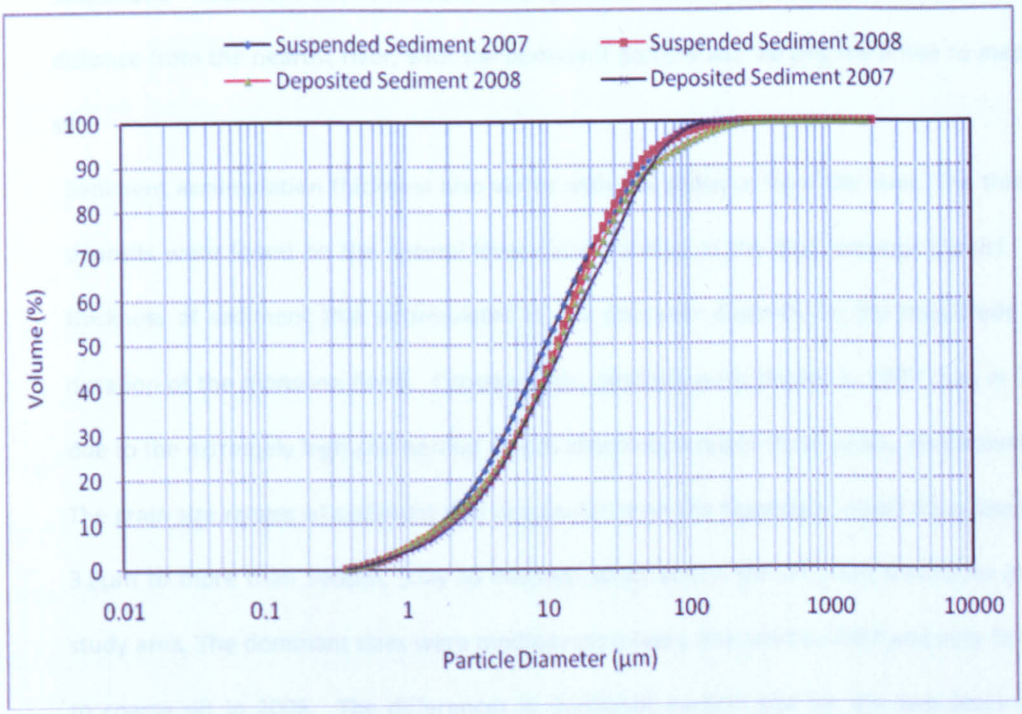


Figure 4.40 Comparison of the grain size composition of suspended and deposited sediment at the back swamp in 2007 and 2008

This chapter has discussed the terrain characteristics, inundation depths and durations, flood velocities, suspended load concentrations and the spatial and temporal patterns of sediment accumulation. The main findings are that:

- The topography of the floodplain is subdued, with only about 3m of relief between highest floodplain ridges and flood basins (*beels*). Based on a DEM developed for the elevation data, the study area has been classified into three main landforms; natural levees of mainly high to medium high land, the back slope consisting of medium high to medium low land and back swamps (*Beels*) which are low to very low land.
- Flood hydraulics (overland flow velocities, inundation depths and durations) were measured and it was found that these hydraulic variables vary as a function of distance from the nearest river or *Khal;*

- Suspended sediment concentrations and particles sizes vary with landform zone and distance from the nearest river, with the dominant particle size varying from fine to *medium* silt;
- Sediment accumulation thickness also varies with the distance from the river. The thickest deposits were found on the natural levees and thinnest in the back swamps (*beels*). The thickness of sediment that accumulates in any one year depends on the magnitude and duration of the monsoon flood. Consequently, deposits were thicker in 2007 than in 2008 due to the extremely high and normal floods which occurred in those years, respectively;
- The grain size ranges of sediment that accumulated on the floodplain varied from less than 3.8μm to more than 500μm, (clay to medium sand) across the different landforms in the study area. The dominant sizes were medium silt to very fine sand in 2007 and very fine silt to coarse silt in 2008. The differences in dominant particle size for the two years were attributable mainly to the contrasting flood hydraulics and the effects of micro-scale topographical variability.
- Sediments were mainly well sorted in both years but most samples were strongly skewed towards the finer fraction sand the particle size distributions were extremely leptokurtic (excessively peaked).

One of the initial premises of the study site is that the type of floodplain vegetation may affect the floodplain sedimentation processes and the characteristics of deposited sediments. The next chapter details the floodplain vegetation types and their impact on sediment processes.

CHAPTER 5 CONTRASTING THE SEDIMENATTION CHARCTERISTICS ASSOCIATED WITH VEGETATION AND FLOODING TYPE

5.1 Introduction

This chapter details how vegetation and flooding type affects floodplain sedimentation processes in terms of particle size characteristics of deposited sediments. To investigate this premise, the field campaign included collection of data on vegetation; naturally grown sun grass (*Imperata cylindrica)* and its interaction with floodplain sedimentation processes and outcomes. It explains the vegetation encountered in the floodplain, their interactions with sediment processes during the monsoon floods of 2007 and 2008 and the resulting impacts on the thicknesses and size distributions (sand/silt or clay) of sediment that accumulated on agricultural land in the study area. It also contrasts the sediment properties (amounts, particle sizes) measured in areas experiencing rainwater and river flooding in 2008. Another important premise is highlighted on the blue green algae (BGA) as a possible source of soil nutrients. Based on cross-tabulation of the monitoring and measurement records for sediment accumulation, particle sizes in sun grass and different agricultural crops, exploratory statistical analysis was employed to explore relationships between these parameters, within the broader context of physical and human interactions in the floodplain.

5.2 Methods of data collection

In 2007, data collection for this study took place in three separate phases during 2007 (Table 5.1) following reconnaissance to identify vegetation site selection, install Astroturf mats along the vegetative buffer strips, mass measuring of blue green algae (BGA), and measurement of the thickness of accumulated sediment on the Astroturf and sampling for particle size analysis (PSA). Astroturf mats were installed to sample sediment accumulation in areas with contrasting natural vegetation (sun grass). The locations of the sites were selected in collaboration with local people based on information about the area flooded each year (even during low monsoon floods and summers with below average rainfall) with minimal disturbance and an absence of artificial obstacles affecting the path of floodwater flow. The natural vegetation (shrubs and grasses; particularly sun grass-*Imperata cylindrica*) was available on the site and adjacent to a distributary channel and land was mostly used for agricultural purpose. The chosen site was easily accessible during the monsoon flood and amenable to sample collection. At the end of the phase the Astroturf was installed in different sites along the front, middle and back vegetation strips.

Table 5.1 Fieldwork performed in six data collection phases in 2007 and 2008

Phase	Duration	Works
Phase-I	15 May - 30 June 2007	• Reconnaissance to identify vegetative site selection; • Astroturf installation along the Vegetative buffer strips.
Phase-II	01 July - 30 Sept. 2007	• Measure the floating blue green algae (mass) in the area inundated by river water
Phase-III	07 - 30 October 2007	• Measure thickness of accumulated sediment from the Astroturf mats and label samples for particle size analysis.
Phase-IV	10 July 08 - 21 July 08	• Install new Astroturf at the same sites as used in 2007; • Installed Astroturf around the rain-fed flooding sites in different agricultural crops.
Phase-V	30 July 08 – 15 Sept. 08	• Measure the floating blue green algae (mass) in the area inundated by river water (same as 2007) and rain-fed flood (only 2008).
Phase-VI	25 Sep 08 – 02 Oct 08	• Measure thickness of accumulated sediment from the Astroturf mats and label samples for particle size

The second (flood) phase centred on measurement of mass of the floating blue green algae (mass) in the area inundated by river water. The third (post-flood) phase consisted of measurement of the thickness of sediment that had accumulated on the Astroturf mats followed by particle size analysis of samples of accumulated sediment at the University of Nottingham.

Fieldwork in 2008 also adopted these procedures, again within a three-phase sequence of works (Table 5.1). However, the context for the fieldwork was different, as due to the lower magnitude of the 2008 monsoon event, river water did not inundate the whole of the study area. This allowed some parts of the study area to be inundated by rainwater in 2008. Hence, in 2008, the area of rain-fed flooding was identified and measurements of sedimentation considering five different agricultural cropping land (which are available during rain water flooding) and measurement of mass of the blue green algae in the floodwater were added to the list of field measurements. Data related framers perception on flooding type and soil fertility was collected through informal discussion and formal questionnaire survey (appendix-A).

5.2.1 Rationale for using Astroturf mats to measure sediment accumulation

A wide range of research has been carried out to quantify long and short-term rates of sediment accumulation on floodplains. Longer-term studies generally span timescales of decades or longer to provide information on floodplain evolution, while 'short-term' studies are performed for periods of a few months up to one or two years with the aim of establishing relationships between flood processes, sediment deposition and floodplain land use (Steiger, *et al.*, 2003). Sediment research is sometimes focused on a specific issue such as investigating contrasts between areas experiencing rainwater and river water flooding or the significance of floodplain vegetation in trapping sediment. In short-term studies, post-event sediment deposition is usually measured relative to a natural or artificial marker horizon that represents the pre-flood ground level. Post-event surveys may involve investigation of naturally occurring or artificial markers using remote sensing, ground-penetrating radar or electromagnetic induction (Magilligan *et al.*, 1998; Walling *et al.*, 1998; Wyżga, 1999). Alternatively, the conveyance loss approach may be employed, although this can only provide tentative estimates of average sedimentation rates (Walling *et al.*, 1986; Walling and Bradley, 1989).

The use of an artificial horizon marker is often preferred as it provides a clearly marked deposition layer, but its accuracy depends on the flow velocity of floodwater being insufficient to redistribute the marker layer through scouring (Richards, 1934; Baumann *et al.* 1984; Kleiss, 1996; Cahoon and Turner, 1989; Reed, 1992; Hupp and Bazemore, 1993; Cahoon and Reed, 1995; Heimann and Roell, 2000).

The use of erosion pins can reduce vulnerability to scouring and so provide reliable estimates of sediment deposition, though the accuracy procured depends on whether the pin size has any impact of the velocity field (Miller and Leopold, 1963; Ranwell, 1964; Aust *et al.*, 1991; Lawler, 1991; Mitchell *et al.*, 1999). Finally, sediment trap approaches employ cylindrical traps, bottles, flat devices and Astroturf mats. Since the 1950s cylindrical–bottle approaches have been used in a wide range of floodplain sedimentation measurement exercises, but this approach has provoked criticism due to the impact of turbulent eddies that disrupt the flow and reduce the accuracy of measured accumulation rates (Mitsch *et al.*, 1979; Bloesch and Burns, 1980; Häkanson and Jansson, 1983; Kronvang *et al.*, 1998; Kozerski and Leuschner, 1999).

Different types of devices, such as plywood boards (Mansikkaniemi, 1985), quasi-flat, fire-clay roof tiles (Brunet *et al.*, 1994, Steiger and Gurnell, 2003), feldspar clay pad markers, plexiglas sediment plates and dendrogeomorphic devices have been used to measure riparian sediment accumulation since the 1980s (Ritchie and McHenry, 1990; Walling *et al.*, 1992; Kleiss, 1996; Heimann and Roell, 2000). Each of the flat devices has generated both positive comment and negative criticism in equal amounts as regards measurement accuracy, depending on the device characteristics and deploying procedures.

Lambert and Walling (1987) used Astroturf mats to measure sediment deposition rates on the floodplain of the River Culm, Devon, UK. After that, a number of researchers have employed similar artificial mats to monitor floodplain sedimentation rates and to determine grain size distributions of the deposited sediment (e.g. Walling and Bradley, 1989; Asselman and Middelkoop, 1995; Simm, 1995; Nicholas and Walling, 1996).

The results produced by these researchers demonstrate that Astroturf mats represent an easily deployable approach, which can trap a substantial proportion of the sediment particles in transport, particularly where the grain size ranges from fine sand to silt. Astroturf mats are easy to install securely on irregular surfaces and can resist high fluid shear stresses while their high 'surface roughness' and 'pliability' act to limit re-erosion of sediment deposited on the mat by floodwater or rainfall runoff. Another important attribute is that the mats are robust, light, and so easily manipulated in the field and laboratory. Thus, Astroturf mats provide a feasible approach to investigating sediment deposition for a range of short-term, sediment investigations (Steiger, *et al.*, 2003). Hence, Astroturf mats were selected in measuring both sediment deposition rates and the grain size distributions of deposited material to investigate the impacts of vegetation strips on sedimentation in areas subject to both riverine and rain-fed flooding.

5.2.2 Astroturf installation along the vegetation buffer strips

During the reconnaissance survey. a particular type of vegetation that seemed to be especially effective in trapping sand was identified in the field through observation and informal interviews with the local farmers. The local name of that vegetation is *Kaissha* and its English name is sun grass (*Imperata cylindrica* (Linn.) Rauschel, Graminea/Poaceae). Two types of sun grass have been considered in this study; the first is *Bon* or *Kaissha* and the other is *Ehar bon*. The sun grass usually found on sandy soils in the natural levee area has thin, individual stems, and is locally known as *bon or kash*. That which grows in thick bunches of stems on the floodplain (where soil is silty), is known as *ehar bon*.

Based on the reconnaissance survey, the effectiveness of sun grass in trapping sediment was selected for close investigation using Astroturf mats (Photograph5.1). In total fifteen Astroturf (20cm diameter) mats were secured on the ground surface in five selected locations at the front, middle and back of vegetation strips to measure the sediment accumulation in June 2007. This procedure was repeated in July 2008 (Figure 5.1 and Photograph 5.2). Thus, 30-sediment samples were collected from the field after floodwater recession in 2007 and 2008. Sediment deposition thicknesses measured on the Astroturf mats and compared of deposition thickness to other four adjacent sites through open digging. The Astroturf samples were bagged and labelled to enable measurement of the volume of accumulated sediment. The total volume of sediment was measured of the accumulated sediment on the Astroturf during flood inundation using standard weight taking methods in the Ecological laboratory at the Department of Botany, Jahangirnagar University in Bangladesh. The sediment from each Astroturf mat was then sampled and labelled according to the site number and carried to the Swinnerton Physical Laboratory at the School of Geography, University of Nottingham, UK, where particle size analysis (PSA) was performed using an LS-coulter counter.

5.2.3 Rain-fed flooding area identification and Astroturf installation

It was only possible to monitor sedimentation in the area of rain-fed flooding during the flood of 2008, which was a normal flood event (*barsha)*. In identifying the area of rain-fed flooding, a base map was prepared using the plot level cadastral map (Scale 16 inches to 1mile). The area delineated on the map based on detailed field observations and surveys backed up by interviews with local farmers. The following criteria were applied when identifying area of rain-fed flooding:

- *The area is not directly connected to the main channel of the anabranch river;*
- The area is low-lying but is bounded by floodplain ridges;
- The area does not experience river flooding in a normal flood event;
- The land has the capacity to retain and store rain water;
- As this is the low-lying area and store the rain water, hence farmers usually cultivate the land for *Aman* paddy, because *aman* paddy can tolerate certain water depth than the *Aus* paddy;
- The land is seasonally flooded, with a duration varying from a few days up to three months;

After identifying the area subject to rain-fed flooding, Astroturf mats were installed at 25 locations to monitor sediment accumulation (Figure5.2 and Photograph 5.2). Monitoring locations were selected using stratified, random sampling. The area of rain-fed flooding was categorised based on the type of agricultural land use during the flood season. Five areas were delineated based on the main crops types and five monitoring sites were allocated to each. Precise locations for the sites within each of the crop types were determined randomly (Table 5.2 and Photograph 5.3).

(a) Native name: *Kash*; Local name: *Bon, Khaishaa,* (*Saccharam Spontaneum.* Linn.), Gramineae

(b) Native name: Boro khash; Local name: *Ehar Bon,* (*Saccharam Spontaneum.* Linn.), Gramineae

Photograph 5.1 (a) and (b) Sun grass - (*Imperata cylindrica* (Linn.)Rauschel, Graminea/Poaceae).

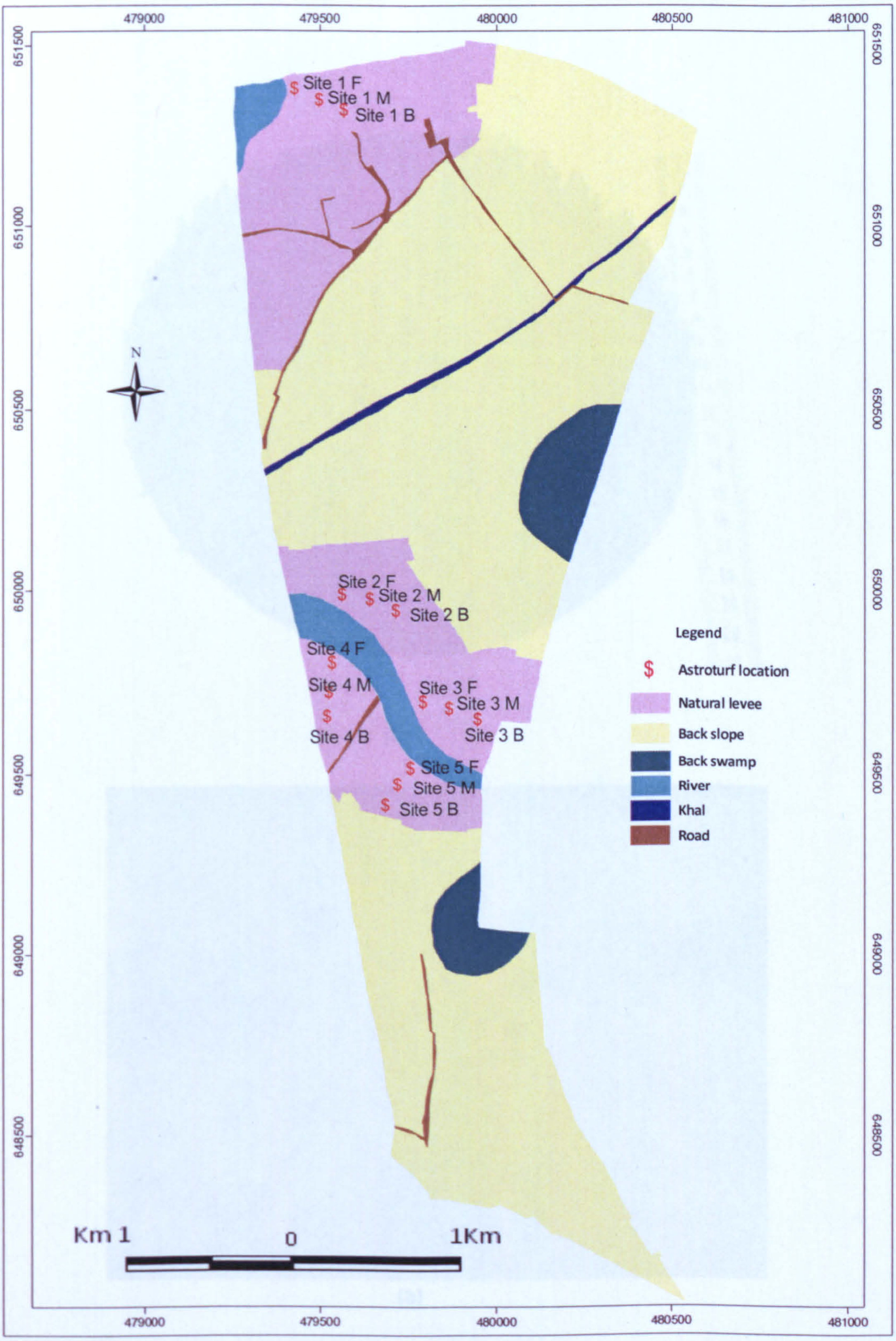
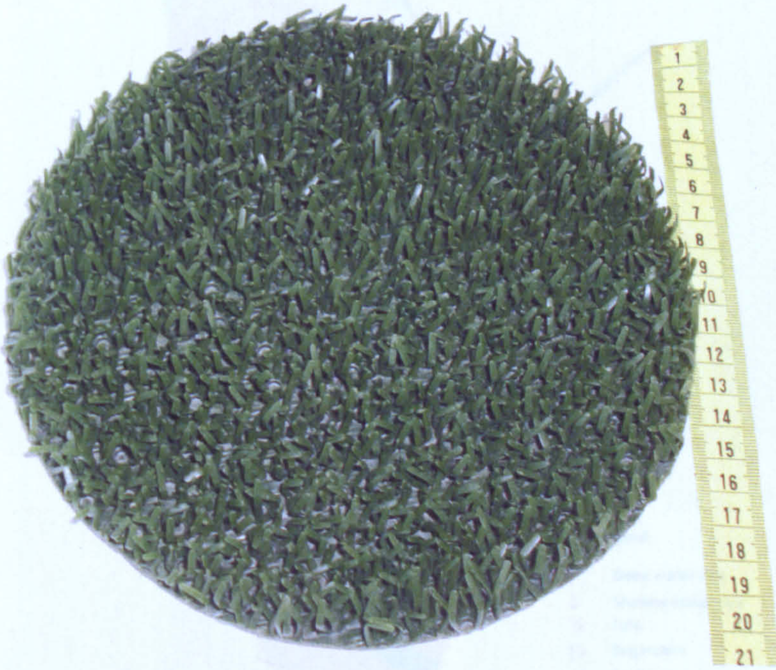


Figure 5.1 Astroturf locations along the vegetated (*Imperata cylindrica* (Linn.)Rauschel, Graminea/Poaceae) strips
[F=Front of the strips, M= Middle of the strips, B= Back of the strips]



(a)

(b)

Photograph 5.2 (a) Astroturf (20cm diameter) to set up on a wooden disc
(b) Astroturf installation in rain-fed (river sediment free) flooding area and along the vegetation strips.

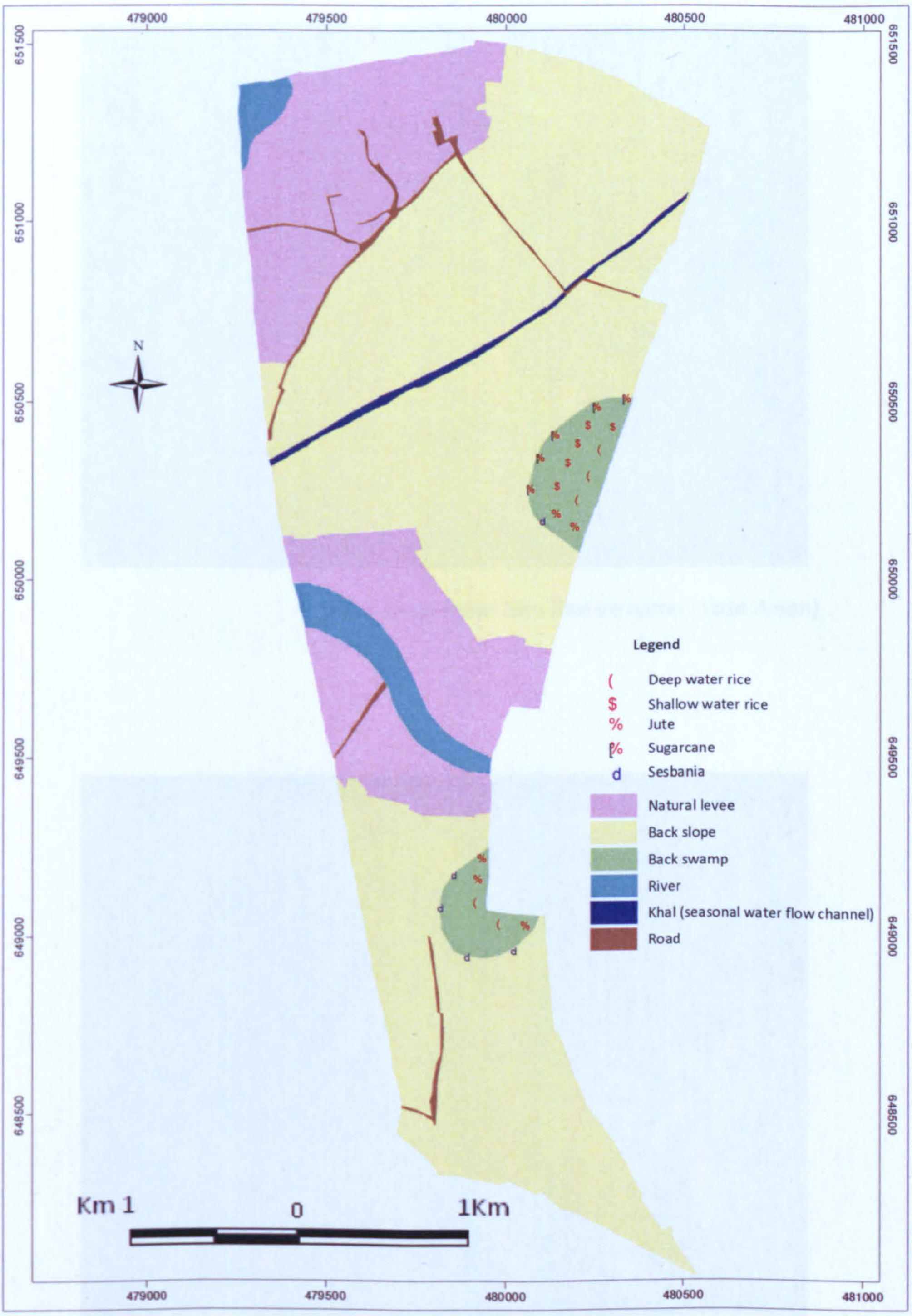
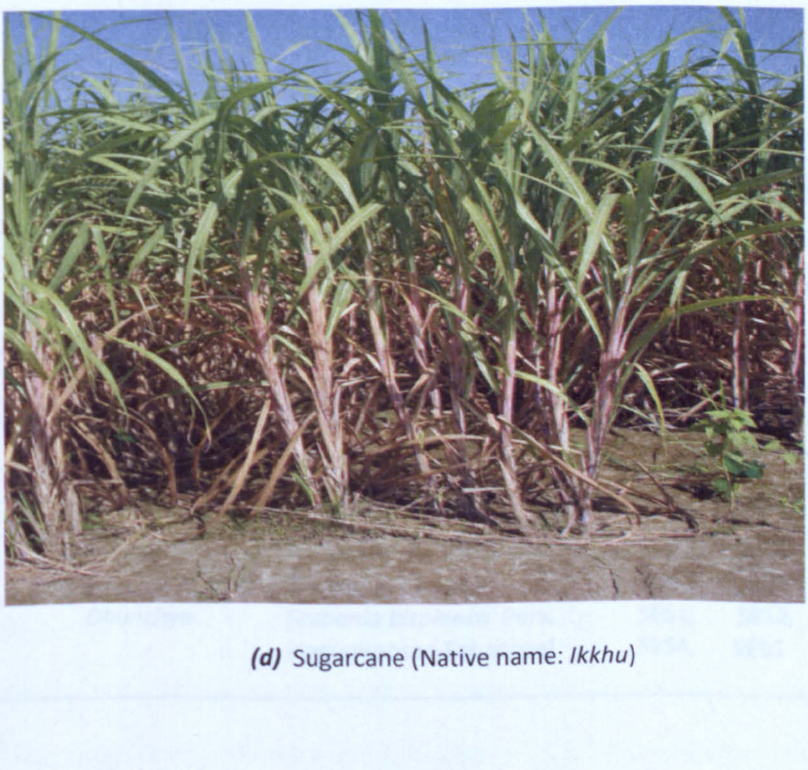


Figure 5.2 Astroturf locations along around the rain-fed flooding sites in different agricultural crops land use

(a) Deep water Rice (Native name : *Vasa Aman*)

(b) Shallow water paddy (Native name: *Diga Aman)*

(c) Jute (Native name : *Paat*)



(d) Sugarcane (Native name: *Ikkhu*)

(e) Sesbania Bispania (Native name: *Dhanchy*)

Photograph 5.3 Astroturf sediment accumulation monitoring sites in the five types of agricultural cropping within the area of rain-fed flooding [(a) Deep water rice; (b) Shallow water rice; (c) Jute; (d) Sugarcane and (e) *Sesbania*].

Table 5.2 Land use categories used to stratify selection of monitoring locations in the rain-fed flooding area

English Name	Local Name	Scientific Name	Sample identification code
Deep water rice	*Vasa Aman*	*Oryza sativa* Linn. (Gramineae)	DWR1, DWR2, DWR3, DWR4, DWR5
Shallow water rice	*Digga Aman*	*Oryza sativa* Linn. (Gramineae)	SWR1, SWR2, SWR 3, SWR4, SWR 5
Jute	*Paat*	*Corchorus capsularis* Linn. (Tiliaceae)	JUT1, JUT2, JUT3, JUT4, JUT5
Sugarcane	*Ikkhu/Akh*	*Saccharum officinarum* Linn. (Gramineae)	SUG1, SUG2, SUG3, SUG4, SUG5
Sesbania	*Dhunchya*	*Sesbania bispinosa* Pers. (Leguminosae-Fabaceae)	SES1, SES2, SES3, SES4, SES5

5.3 Analysis and Results

This section presents techniques employed in data analysis. Analyses were performed to elucidate the interactions between the vegetative buffer strips and sedimentation, contrasts between rainwater and river flooding in sediment characteristics and an importance of blue green algae. The approach employed exploratory statistical analysis, coupled with bivariate and geo-statistical techniques, performed within Arc-GIS (version 9.2).

5.3.1 Effect of vegetated buffer strips on sedimentation

In the field it was observed that sun grass and Saccharum (*Imperata arundinaceae, Imperata cylindrica* and *Saccharam Spontaneum*) appeared to be highly effective in trapping the flood borne sediment (Photograph 5.1). However, farmers usually harvest this type of vegetation prior to the flood season for various uses including cattle feed, roofing, fencing and fuel. Farmers clear these grasses primarily to extend the land area available for planting subsistence or cash crops. They do this during the pre-monsoon period because these grasses are deep rooted, making it necessary to remove them before the area is cultivated. Generally, sun grass species are regarded as being far less important than cash, food or even subsistence crops.

However, it was observed that the presence of these grasses can actually be beneficial to farmers, firstly, by reducing the velocities of flood waters flowing into and across the floodplain and, secondly, by trapping a substantial proportion of the coarse grained sediment carried by the flood water while allowing the finer grained sediment to pass through. As result, where sun grass was encountered on the natural levee a significant amount of coarse grain sediment (which is unsuitable for agricultural cultivation and may result in land having to be left fallow in the following season) was deposited within the sun grass – which acted as a flow and sediment buffer (Photograph 5.4). This resulted in the agricultural land downstream receiving finer grained sediment that rendered it more suitable for cultivation. The buffering effect was observed to be effective even for strips of grass only 10 to 20 metres wide.

Table 5.3 lists the thicknesses and grain size characteristics measured at five study sites within and around grassy buffer strips, during the 2007 and 2008 floods. The amounts and sizes of sediment deposited varied with location (in front of, within and behind the strip) and year. In 2007, the greatest thickness of deposited sediment (4.5cm) was recorded in front of a grass strip, while the thinnest deposition (0.9cm) occurred behind a strip. This was also the case in 2008, the equivalent figures being 3.1cm and 6.5cm, respectively (Figure 5.3). In terms of mass per unit area, average sediment accumulation was 861 t ha^{-1} in front of the grass strips, falling to 437.5 t ha^{-1} within them and 344.75 t ha^{-1} behind the back of vegetation strips, in 2007. Smaller amounts of sediment accumulated in 2008, the equivalent figures being 507.5 t ha^{-1} , 306.25 t ha^{-1} and 169.75 t ha^{-1} , respectively.

PSA of accumulated sediments revealed wide variations in the diameters of deposited grains as a function of location relative to the buffer strips (Table 5.3). In 2007, the average median diameter (D_{50}) of deposited sediment sampled in front of, within and behind the grass strips varied from 83µm (very fine sand), to 28µm (medium silt) and 22µm (medium silt). The equivalent figures for 2008, were 83µm (very fine sand), 31µm (medium silt) and 19µm (medium silt), respectively. The D_{90} values showed a similar pattern, declining from 192µm (fine sand) to 139µm (fine sand) and then to 95µm (very fine sand) across the buffer strips in 2007 and

Table 5.3 *Sediment thickness and grain size variation recorded around grass buffer strips*

Sample sites	Year	Front of the traps			Middle of the traps			Back of the traps		
		Thickness (cm)	D_{50}	D_{90}	Thickness (cm)	D_{50}	D_{90}	Thickness (cm)	D_{50}	D_{90}
Site-1	2007	4.50	81.09	191.60	2.50	28.42	94.62	1.50	21.50	138.60
	2008	3.10	83.65	202.70	1.75	31.20	101.10	1.00	18.03	106.00
Site-2	2007	3.75	81.47	186.30	2.20	28.74	114.80	1.25	21.38	115.1
	2008	2.90	83.89	205.20	1.10	32.74	111.40	0.95	17.87	98.57
Site-3	2007	3.50	84.58	204.50	1.80	23.33	139.40	1.10	20.83	100.10
	2008	2.65	82.20	190.90	1.25	29.47	96.14	0.85	19.94	126.20
Site-4	2007	3.25	80.28	202.90	2.10	28.66	91.77	1.30	21.75	113.50
	2008	2.40	83.16	207.00	1.40	31.77	104.30	0.75	21.51	139.30
Site-5	2007	3.10	89.98	223.00	2.00	30.13	106.90	0.90	22.52	128.4
	2008	2.20	82.44	196.60	1.00	31.01	106.80	0.65	18.07	100.50

(a) Flow resistance associated with sun grass slows flood water velocities

(b) Sun grass traps coarse sediment carried by the flood water

Photograph 5.4 (a) and (b) Flow slowing and sediment trapping by sun grass buffer strips.

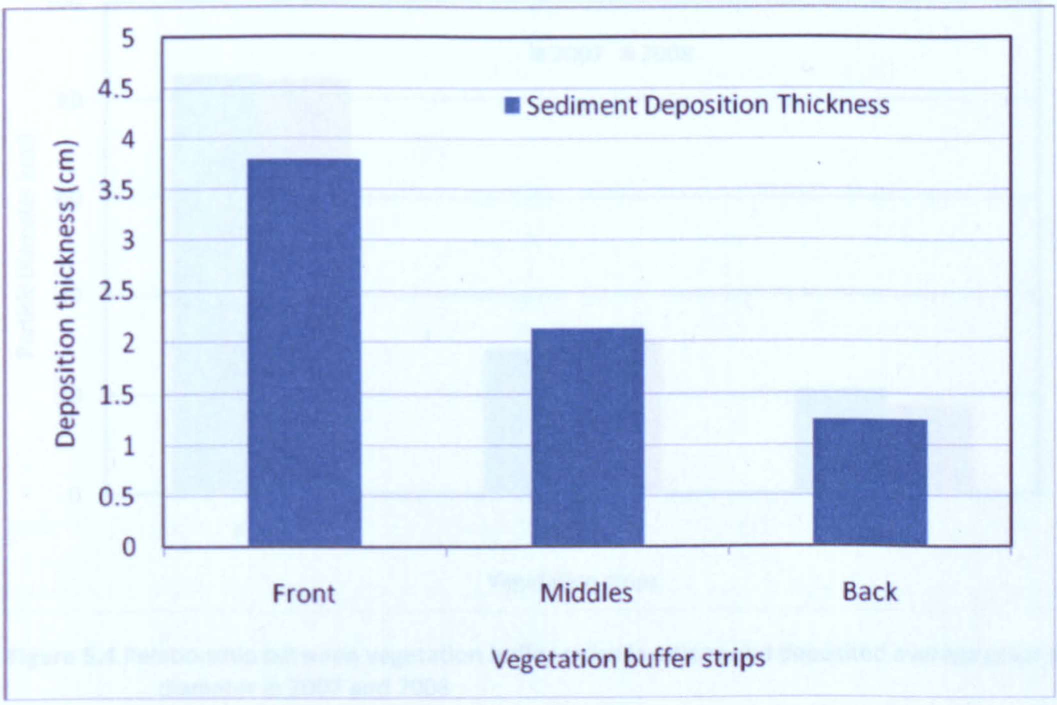


Figure 5.3 Variation in average deposition thickness around grass buffer strips

203μm (fine sand), 106μm (very fine sand) and 101μm (very fine sand), in 2008. The average grain sizes of deposited sediment in the front, middle and back of the vegetation stripes is shown in figure 5.4. A strong positive correlation was evident between the vegetation strip locations and deposited particle diameter, although visual examination of the relationship between the variables suggest that comparatively coarse grain particles are deposited at the front of the vegetation strips and gradually finer particles are found behind the strips(Figure 5.4).

In summary, both the amount and calibre of sediments deposited on the floodplain were found to decline as water flowed through the buffer strip in both years of observation. These findings indicate that even a relatively narrow strip of natural vegetation (Sungrass - *Imperata cylindrica* (Linn.) Rauschel, Graminea/Poaceae) can be effective in trapping sediment. It follows that buffer strips could potentially be used to protect agricultural fields from sand deposition, while still allowing for the annual accumulation of silt that is beneficial to soil fertility and productivity.

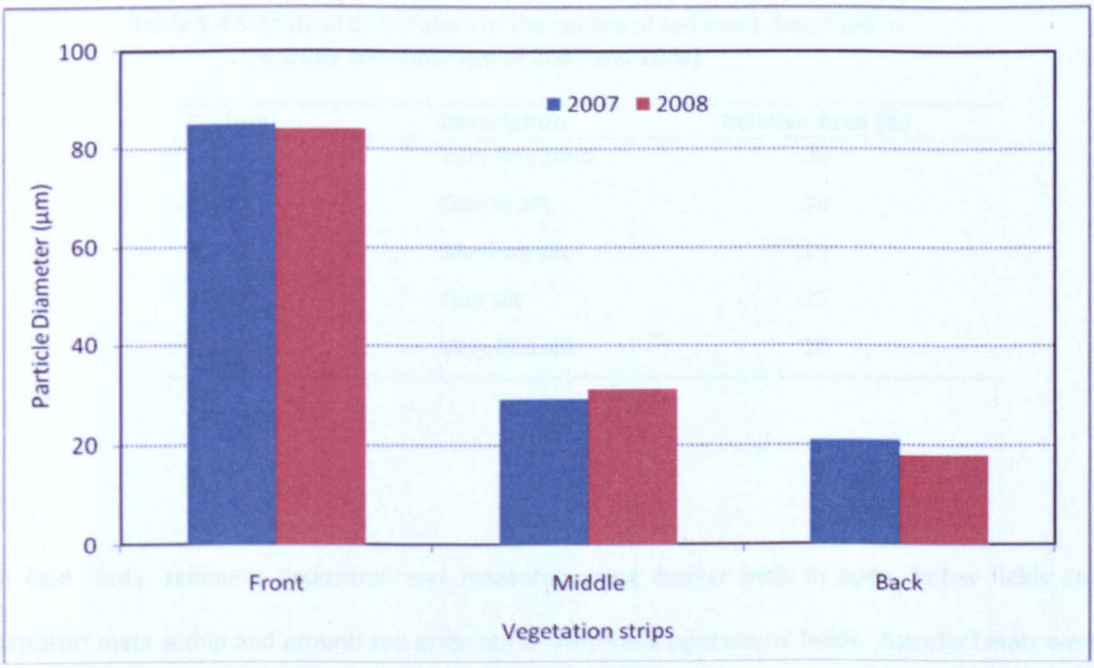


Figure 5.4 Relationship between vegetation buffer strips locations and deposited average grain size diameter in 2007 and 2008

The spatial distribution of sedimentation throughout the study area was also investigated based on measurements of recently accumulated deposits, using a kriging method for geostatistical analysis. Kriging was used to interpolate median grain size (D_{50}) between measurement sites distributed across the study area and results are shown in Figure 5.5 and listed in Table 5.4.

Figure 5.5 demonstrates interpolation of median grain size (d50) throughout the study area. This map was produced using the kriging method in Arc view geo-statistical analysis. The data refer to Astrofurf measurements of median grain sizes averaged for 2007 and 2008 and binned into five size classes.

The results plotted in the map and listed in Table 5.4 show that, on average, sand (>50μm) was deposited on about 30% of the study area, followed by fine silt (21-30μm) on 25% of the area, coarse silt (41-50μm) on 20%, medium silt (31-40 μm) on 15%, and very fine silt (<20μm) on 10% of the land.

This spatial analysis is important in that it reveals that almost a third of the study area currently experiences deposition of agriculturally-damaging sand rather than beneficial silt. This emphasises the potential for buffer strips to be used to manage sand deposition in agricultural areas, with the aims of: avoiding land having to be left fallow due to sand deposition; improving soil fertility; allowing farmers more choice over the crops they select, and; increasing agricultural productivity generally.

Table 5.4 Statistical distribution of the calibre of sediment deposited in the study area (average of 2007 and 2008)

D_{50} (μm)	**Description**	**Relative Area (%)**
> 50	Very fine sand	30
41-50	Coarse silt	20
31-40	Medium silt	15
21-30	Fine silt	25
< 20	Very fine silt	10

In field study, sediment deposition was measured using marker beds in open, fallow fields and Astroturf mats within and around sun grass buffer strips and agricultural fields. Astroturf mats were used in vegetated areas because clearing an area of ground to create a marker bed would disturb the velocity field in the flood water, generating local sediment deposition and invalidating the recorded results. Also, the smaller size of the Astroturf mats (20 cm^2) made it easy to deploy them even in relatively densely vegetated areas. However, thicknesses of sediment recorded using Astroturf mats are not directly comparable marker beds. This is the case because the artificial grass of the Astroturf occupies some of the space above the mat, reducing the volume of deposited sediment per unit thickness compared to that accumulated on a marker bed. Consequently, a given volume of deposited sediment will generate a greater thickness when measured using an Astroturf mat than it would if measured using a marker bed.

It was, therefore, necessary to correct the sediment thicknesses recorded using Astroturf mats to allow for the volume of the artificial grass stems. The correction was based calculating the equivalent marker bed thickness using the equations:

$$T = \frac{\nu}{\pi r^2}$$

Where, T = Equivalent Thickness of sediment of Astroturf mat, ν = Total mass of sediment on the Astroturf, πr^2 = Area of Astroturf mat, π = 3.142 and r = radius of the mat 10cm.

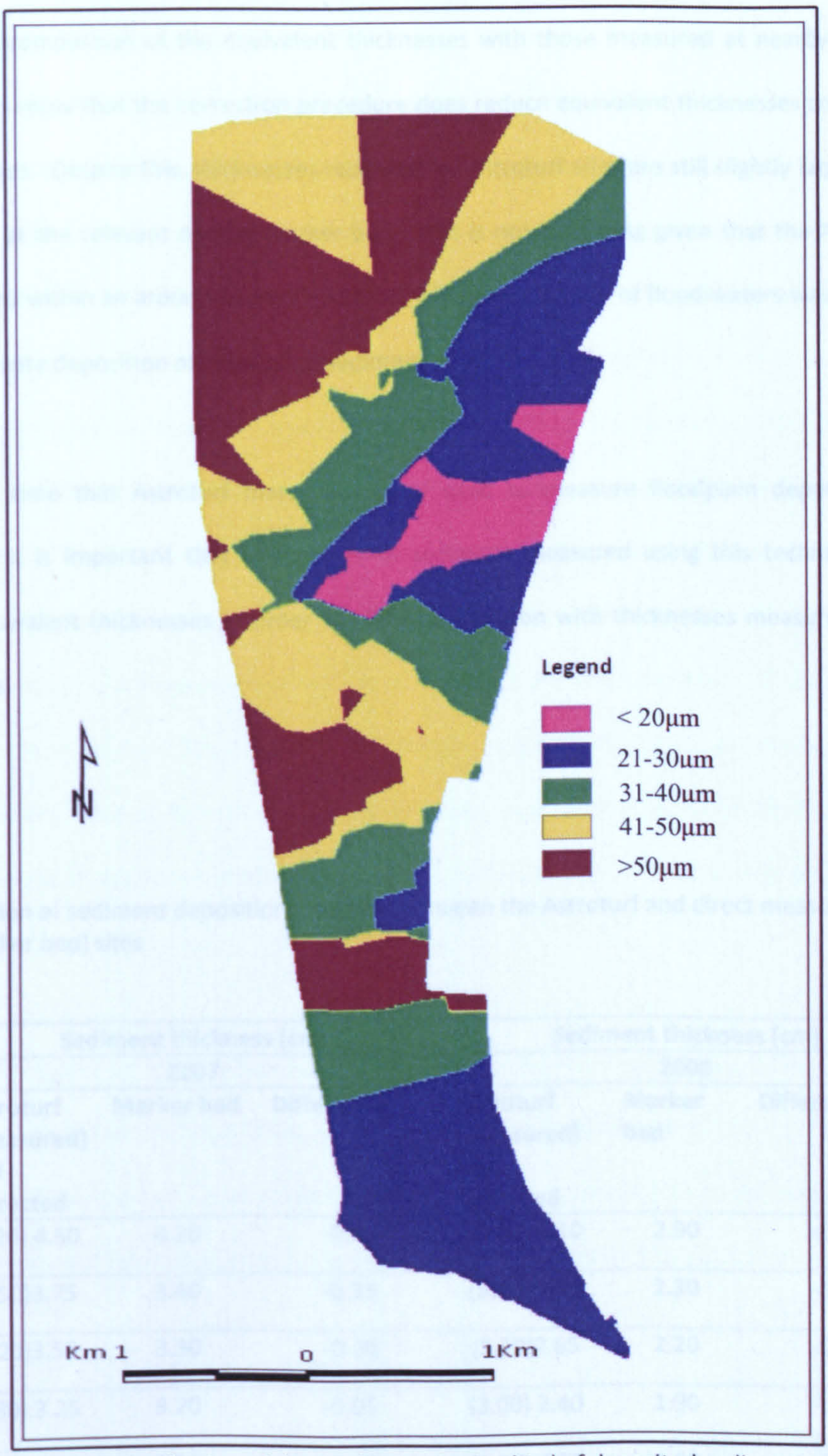


Figure 5.5 Distribution of the median grain size (D_{50}) of deposited sediment over the study site

Table 5.5 illustrates the outcomes of application of the correction procedure for selected Astroturf mats and allows comparison of the equivalent thicknesses with those measured at nearby marker beds. The results show that the correction procedure does reduce equivalent thicknesses compared to measured values. Despite this, thicknesses recorded for Astroturf sites are still slightly larger than those measured at the relevant nearby marker bed. This is not surprising given that the Astroturf mats were located within an around vegetation strips, where retardation of flood waters was visually observed to promote deposition of suspended sediment.

This is the first time that Astroturf mats have been used to measure floodplain deposition in Bangladesh and it is important that thicknesses of sediment measured using this technique are corrected to equivalent thicknesses in order to allow comparison with thicknesses measured using other techniques.

Table 5.5 Variation of sediment deposition thickness between the Astroturf and direct measurement (marker bed) sites

Sample sites	Sediment thickness (cm) 2007			Sediment thickness (cm) 2008		
	Astroturf (measured) and corrected	Marker bed	Difference	Astroturf (measured) and corrected	Marker bed	Difference
Site-1	(5.20) 4.50	4.20	-0.30	(3.80) 3.10	2.90	-0.20
Site-2	(4.50)3.75	3.40	-0.35	(3.50) 2.90	2.30	-0.60
Site-3	(4.20)3.50	3.30	-0.20	(3.20)2.65	2.20	-0.45
Site-4	(3.80) 3.25	3.20	-0.05	(3.00) 2.40	1.90	-0.50
Site-5	(3.70)3.10	3.00	-0.10	(3.00) 2.20	1.70	-0.50
Average	(4.28) 3.62	3.42	-0.20	(3.30) 2.65	2.20	-0.45

[Note: Number in parentheses denotes sediment deposition thickness on the Astroturf mat measured in the field]

5.3.2 Interactions between agricultural crops and sedimentation

Most of the farmers interviewed recognised that sun grass can trap sediment but did not employ buffer strips because they reduce area available for growing food crops. They pointed out that they need to produce enough food crops to meet subsistence levels, and that meant that land could not be spared for sun grass buffer strips. However, over 70% of farmers were concerned about the deposition of sand on their crops fields during the monsoon. Consequently, field research was performed to investigate interactions between different crops and the quantities and calibres of sediment trapped within a plot. Five common agricultural crops were available for investigation during the monsoon season. These were deep-water paddy (*vasha aman*), shallow water paddy (*dhigha aman)*, Jute (*paat)*, sugarcane (*akh)*, and Sesbania (*dhunchya)* (Photograph 5.3), all of which are known to be effective in trapping sediment (Photograph 5.5 and 5.6). The width of plots planted with different crops varied from 30m to 60m (60m for sugarcane, 50m for deep water paddy, 40m for jute, 30m for shallow water paddy and sesbania) and average plot width being 42 m. The field survey monitored variations in sediment deposition thickness, total mass of sediment, and particle size distribution (Table 5.6).

Deposition was greatest in the shallow water paddy field where 45 and 30mm of accumulated sediment were recorded in 2007 and 2008, respectively. The equivalent figures for the other crops were: deep water paddy 35 and 23mm, sugarcane 22 and 11mm, *sesbania* 18 and 9mm, and jute 15 and 8mm. On average 27mm of sediment was trapped in 2007, compared to just 16mm in 2008 – a 40% reduction.

The mass of deposited sediment per unit area was also greatest in the shallow water paddy field in both years (437.5 t ha^{-1} and 280.0 t ha^{-1} in 2007 and 2008, respectively). The equivalent figures for the other crops were: deep water paddy 350.0 t ha^{-1} and 262.5 t ha^{-1} , sugarcane 262.5 t ha^{-1} and 140.0 t ha^{-1}, jute 175.0 t ha^{-1} and 122.5 t ha^{-1}, and sesbania 140 t ha^{-1} and 105 t ha^{-1} . The average mass deposition rate was 273.0 t ha^{-1} in 2007, decreasing by 33% to 182.0 t ha^{-1} in 2008.

There were also marked differences in the calibre of sediment trapped by the various crops. Of the sediment that accumulated in the shallow water paddy field in 2007, 54% was sand, 41% silt and 5% clay, while deposited sediment was noticeably finer in 2008 (the equivalent figures being 37%, 50% and 13%).

Inter-annual differences in sediment calibres recorded in the other crops were less marked (Table 5.6). Particle size analyses were performed to investigate how the degree of sorting varied between the different depositional environments (Figures 5.6 to 5.10 and Table 5.7).

Generally, shallow water paddy and jute crops trapped coarser grained sediment in both years. The standard deviations (σ) were all greater than 4, indicating that deposited sediments were extremely poorly sorted in all five agricultural crops during both monsoon seasons. However, sorting was slightly better (that is, the standard deviation was about 7% lower) in 2008 compared to 2007. Skewness values indicate that particle size distributions were strongly skewed towards finer grain size in both years, with no marked differences between crops. Kurtosis values reveal extremely leptokurtic distributions for all crops and in both years.

The median diameter (D_{50}) of deposited sediment suggests a significance variation between the year and crops. In 2007, 50% of the particle size found finer than 60μm (coarse silt) of shallow water paddy, 25μm (medium silt) of deep-water paddy, 50μm (coarse silt) of jute, 40μm (coarse silt) of sugarcane and 40μm (coarse silt) of sesbania. In 2008, it followed as 35μm (coarse silt), 20μm (medium silt), 60μm (coarse silt), 45μm (coarse silt) and 55μm (coarse silt) of the same crops land (Figure 5.6 to5.10).

Figures 5.11 and 5.12 show cumulative size distribution curves in 2007 and 2008 respectively. These plots make clear that the main difference between the crops lies in the silt size range. For example, in 2007, about 85% particles trapped by deep water paddy were of silt size or finer, but only 55% particles trapped by shallow water paddy were silt or finer. Clearly, shallow water paddy was more likely to trap sand than deep-water paddy. Particle size distributions for the other three crops in 2007 are intermediate between those for deep and shallow water paddy. Similar trends are apparent in the data for 2008. It also shows that median diameter (D_{50}) of the particle size is finer than 65μm (very fine sand) of shallow water paddy, 50µm (coarse silt) of jute, 45µm (coarse silt) of sesbania, 40µm (coarse silt) of sugarcane and 23µm (medium silt) of deep water paddy in 2007. In 2008, it flowed by 60µm (coarse silt) of jute, 55µm (coarse silt) of sesbania, 45µm (coarse silt) of sugarcane, 38µm (coarse silt) of shallow water paddy and 22µm (medium silt) of deep water paddy.

Photograph 5.5 Relatively coarse sediment deposited in an area of shallow water *aman* paddy during flooding in 2007

Photograph 5.6 Relatively coarse sediment deposited in an area of shallow water *aman* paddy during flooding in 2008

Table 5.6 Characteristic of sediment deposited in 2007 and 2008

Agricultural land use	Plot width (m)	Sediment Thickness(cm)		Mass per unit area (t ha^{-1})		Size distribution (%)					
						Clay (<3.9µm)		Silt (3.9-63µm)		Sand (>63µm)	
		2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Deep water paddy (*vasha aman*)	50	3.5	2.3	350.0	262.5	11	15	69	65	20	20
Shallow water paddy (*dhigha aman*)	30	4.5	3.0	437.5	280.0	5	13	41	50	54	37
Jute (*paat*)	40	1.5	0.8	175.0	122.5	6	5	37	43	57	52
Sugarcane (*akh*)	60	2.2	1.1	262.5	140.0	9	9	54	50	37	41
Sesbania (*Dhunchya*)	30	1.8	0.9	140.0	105.0	7	6	54	47	39	47
Average	42	2.7	1.62	273.0	182.0	8	10	51	51	41	39
Inter-annual variation (%)		- 40		-33		+25		0		-5	

Table 5.7 Variability on sediment sorting characteristic measured in 2007 and 2008

Land use of agricultural crops	Sorting (µm)									
	Standard Deviation		Skewness		Kurtosis		D_{50}		D_{90}	
	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Deep water paddy (*vasha aman*)	55	46	3	2	15	8	26	26	103	100
Shallow water paddy (*dhigha aman*)	96	76	4	4	34	23	72	44	189	144
Jute (*paat*)	69	65	2	3	11	16	59	47	157	143
Sugarcane (*akh*)	57	57	2	2	9	4	47	46	135	137
Sesbania (*Dhunchya*)	64	71	3	3	13	21	53	62	146	157
Average	68	63	3	3	16	15	51	45	146	136
Variation (%)	-7		0		-6		-12		-7	

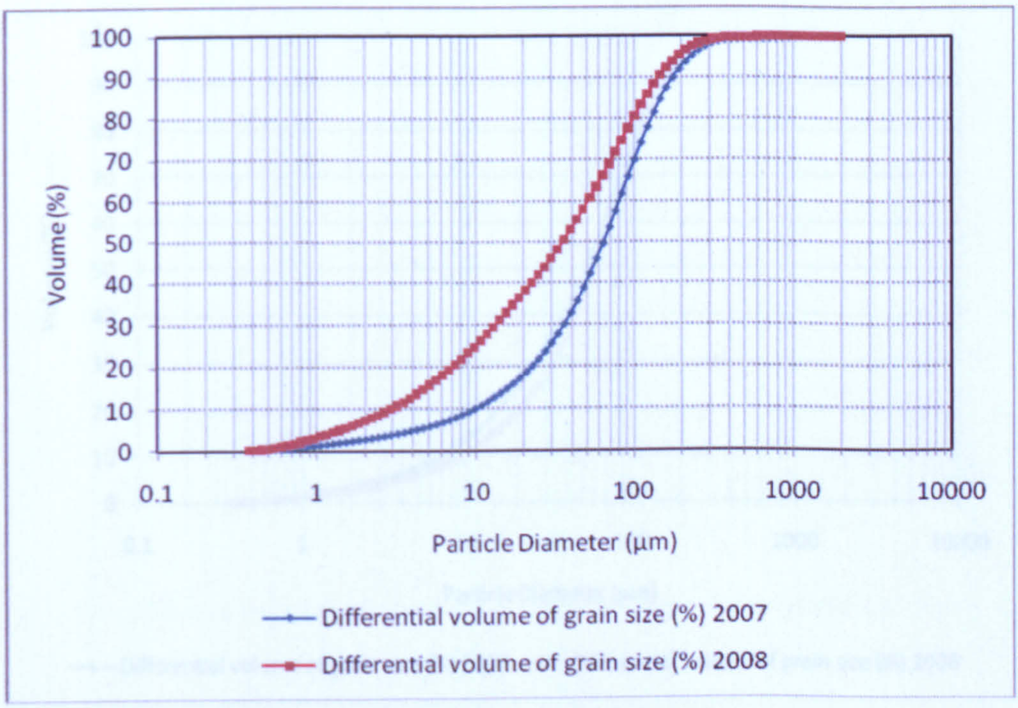


Figure 5.6 Grain size distributions measured in the shallow water paddy field

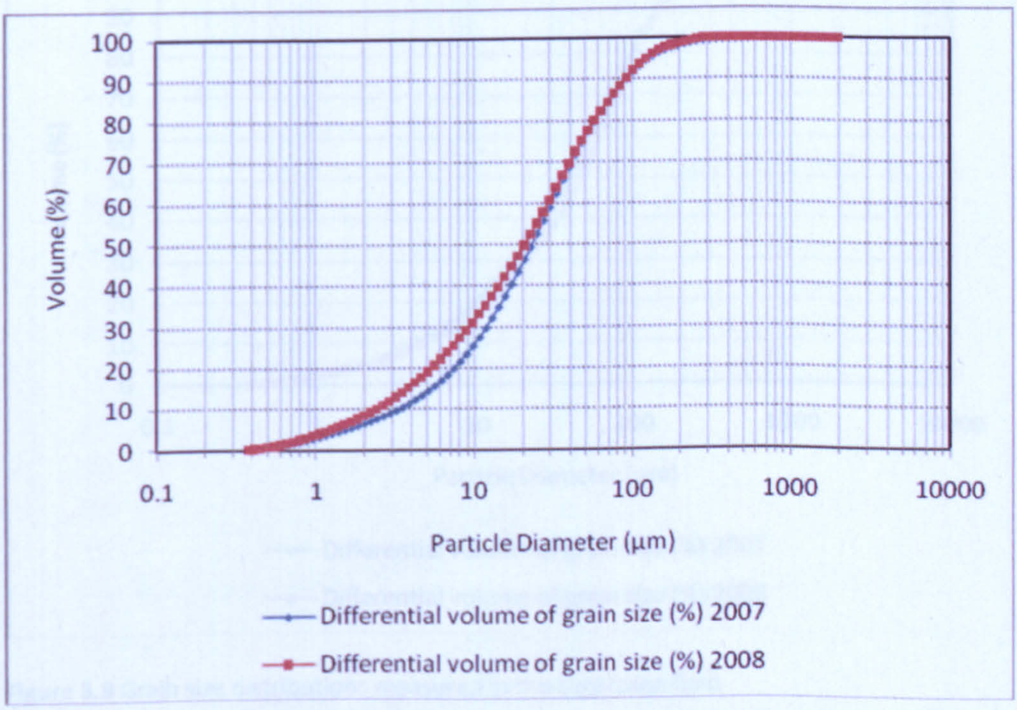


Figure 5.7 Grain size distributions measured in the deep-water paddy field

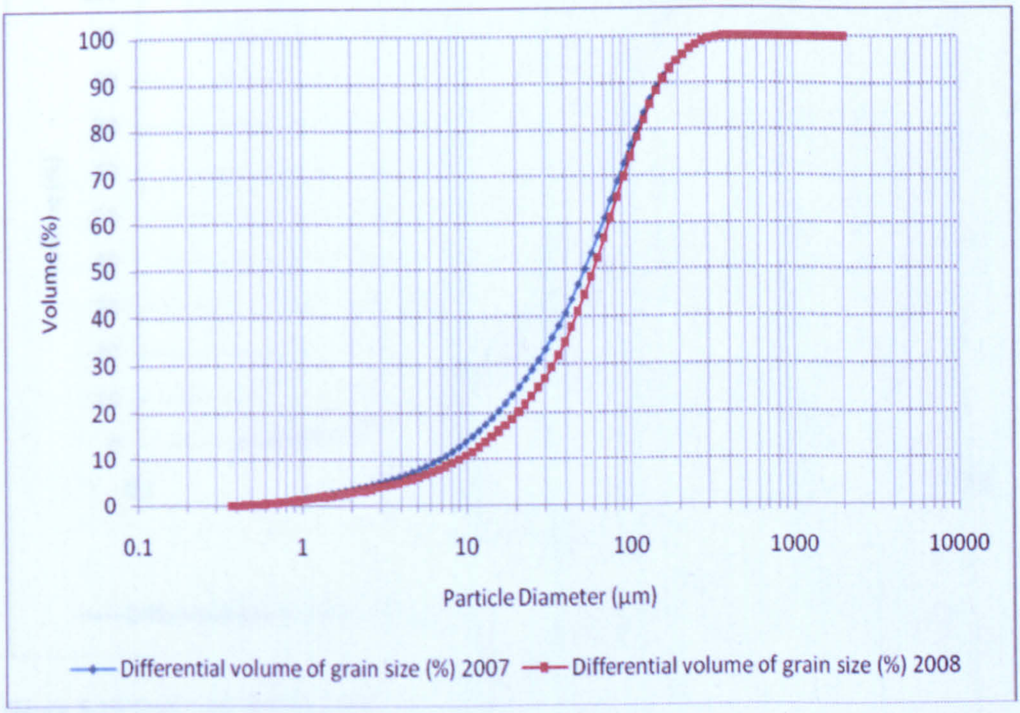


Figure 5.8 Grain size distributions measured in the jute field

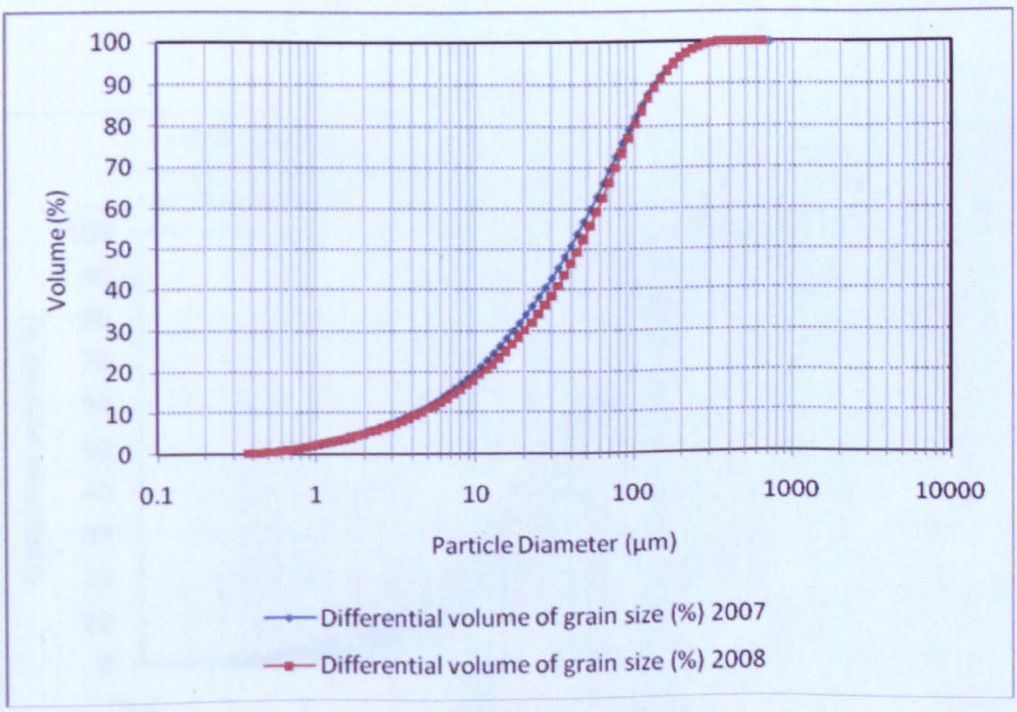


Figure 5.9 Grain size distributions measured in the sugarcane field

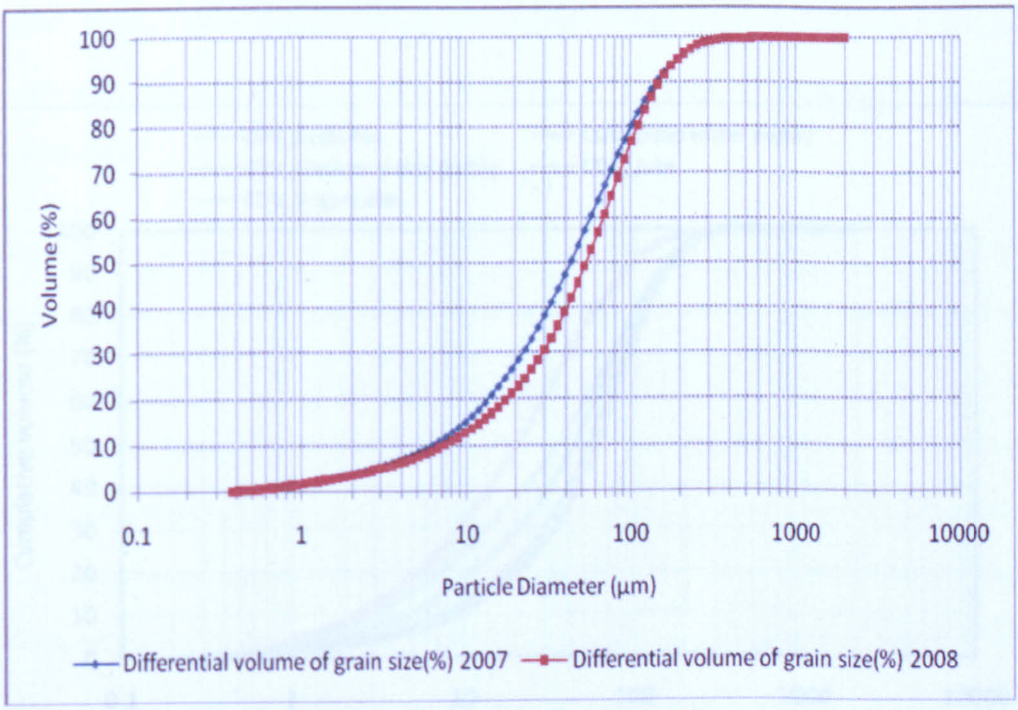


Figure 5.10 Grain size distributions measured in the sesbania field

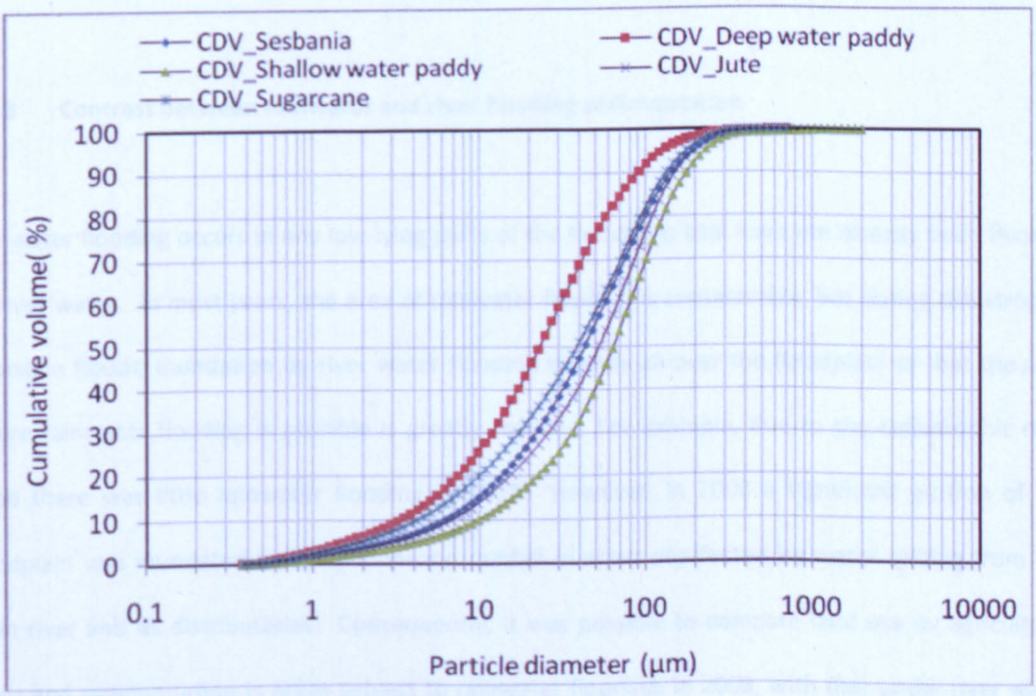


Figure 5.11 Particle size distributions (cumulative %) for five different types of crops in 2007

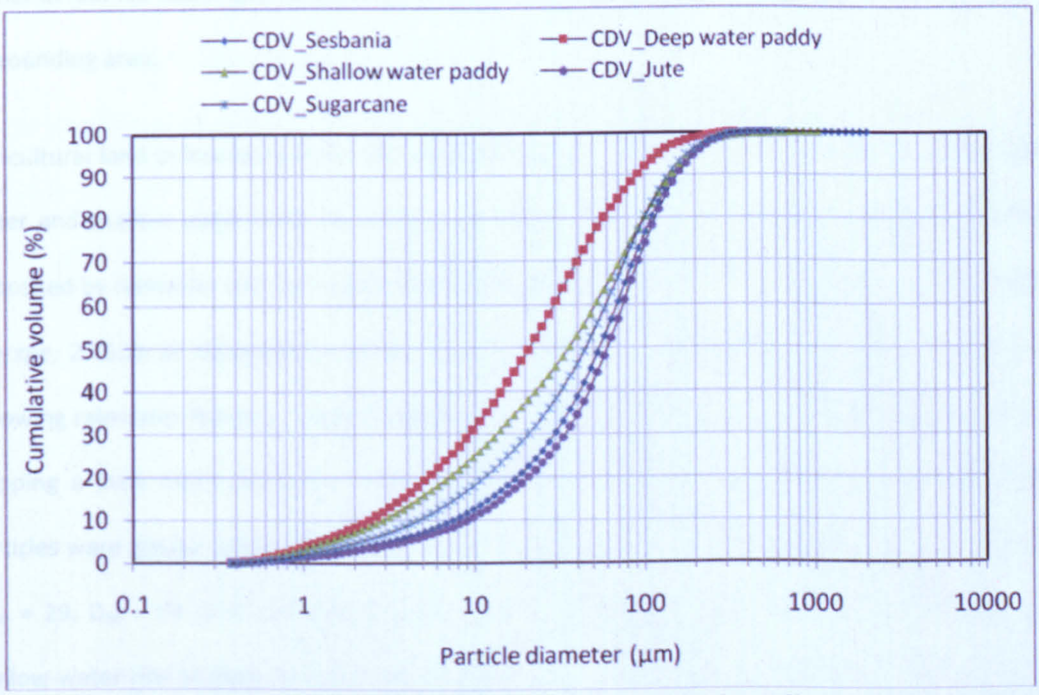


Figure 5.12 Particle size distributions (cumulative percentage) for five different types of crops in 2008

5.3.3 Contrast between rainwater and river flooding sedimentation

Rainwater flooding occurs in any low-lying parts of the floodplain that have not already been flooded by river water. In most years, the area of rainwater flooding is considerable, but during catastrophic monsoon floods, inundation by river water flooding extends all over the floodplain so that the area where rainwater flooding is possible is greatly reduced. For example, due to the catastrophic river flood there was little rainwater flooding in 2007. However, in 2008 a significant portion of the floodplain was inundated by early monsoon rainfall in areas unaffected by water spilling from the main river and its distributaries. Consequently, it was possible to compare land use by agricultural crops and sedimentation in areas subject to rainwater flooding, in 2008, with that under river water flooding, in 2007.

Rain fed flooding is the inundation of the land mainly by monsoon rainwater. The sediment of the rain fed flooding, comes from the adjacent high land like natural levees, settlements, roads, and even very gently sloping land and accumulation take place in the low-lying area. The agricultural yield is higher in rain fed flooding area because the sediment is rich in organic matter as it is wash load of the surrounding area.

Agricultural land in low-lying areas was primarily planted with local varieties of *aman* paddy (deep-water and shallow water rice), resulting in variations in the thickness and grain sizes of sediments deposited by rainwater and river water flooding, respectively (Table 5.8, Photograph. 5.5 and 5.6). On average, 2.75cm of deposition occurred under river water flooding, but only 1.7cm was observed following rainwater flooding. Agricultural land use had a secondary impact, with shallow-water rice trapping a little more sediment than deep-water varieties. The average diameters of deposited particles were greater under river water inundation (D_{50} = 53, D_{90} = 125 μm) than rainwater flooding (D_{50} = 29, D_{90} = 54 μm). Agricultural land use also had a secondary impact on particle size, with shallow-water rice tending to trap sediment that was a little coarser than that found in deep-water varieties. In Table 5.8, only two agricultural crops were presented because these are the most common crops that farmers cultivate in both rainwater and river water-flooding conditions. This table is only shows the specific scenarios of the effeciecny of deep water and shallow water rice in trapping sediment at different flooding levels. Therefore, the data might differ in respect of others crops and flooding conditions.

Table 5.8 Comparison of average thicknesses and grain sizes of sediment deposited under rainwater and river water flooding, depending on agricultural land use

English name	Scientific name	Thickness (cm)		D_{50} (μm)		D_{90} (μm)	
		River water	Rain water	River water	Rain water	River water	Rain water
Deep water rice *(Vasha Aman)*	*Oryza sativa Linn.* (Gramineae)	2.5	1.5	45	28	110	60
Shallow water rice *(Digha Aman)*	*Oryza sativa Linn.* (Gramineae)	3	1.9	60	30	139	48
Average		2.75	1.7	53	29	125	54

The particle size distribution for sediments deposited by river water flooding was unimodal, while that for rainwater flooding was bimodal (Figure 5.13). The main modes are associated with sediment transported as wash load by floodwaters regardless of how the flood is derived. The secondary mode in the size distribution for rainwater deposited sediments probably represents relatively coarse sediment that has been eroded from the surrounding agricultural fields, floodplain ridges and road embankments by surface runoff and carried into the low-lying areas as bed material load.

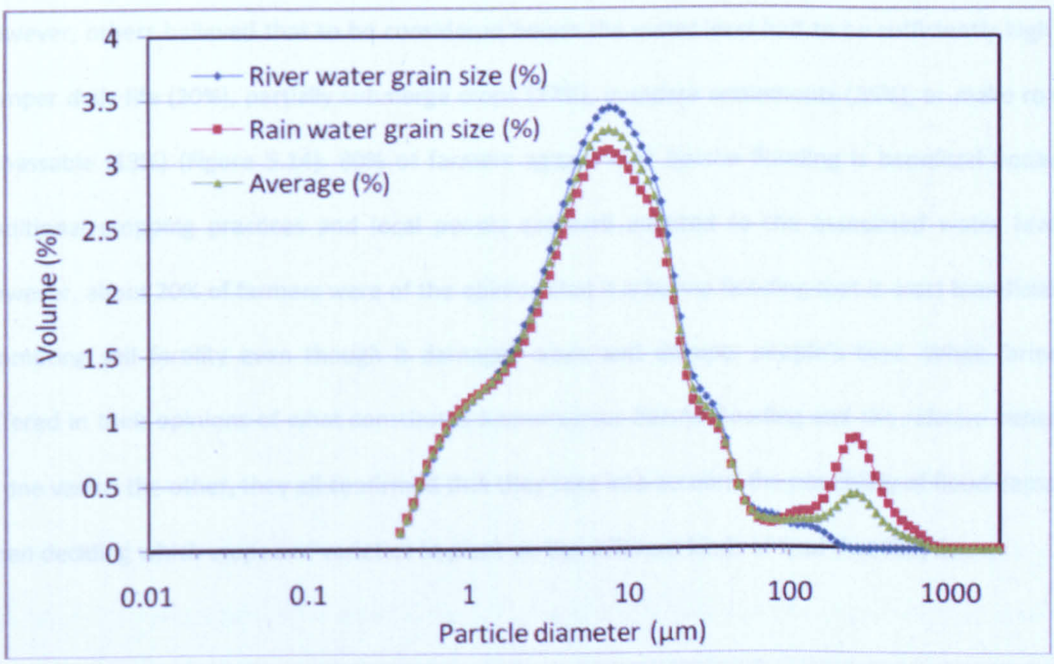


Figure 5.13 Particle size distributions of sediments deposited by river and rain water flooding

Descriptive statistics produced by PSA further characterise the deposited sediments. Mean grain sizes of 35μm (coarse silt) and 26μm (medium silt) for river water and rainwater flooding confirm that river borne flood sediments were slightly coarser. Standard deviations of 88 for river borne and 20 for rainwater borne sediments indicate that the former were poorly sorted compared to the moderately sorted rain borne sediments. Skewness values of 3.97 and 2.25 indicate that sediments deposited by both types of flooding were strongly skewed towards fine particles, while kurtosis values of 17 and 12 both represent extremely leptokurtic (peaked) distributions.

5.3.4 Farmer's perceptions about flooding and soil fertility

Farmers throughout Bangladesh distinguish between floods that are normal (*barsha*) and extreme (*bonna*). Generally, flooding is regarded as *barsha* provided that it does not damage crops or disrupt people's lives, in which case it is considered to be *bonna*. However, the distinction is not always clear. In the survey of local farmers, 35% of those questioned thought complete submergence of agricultural crops was sufficient to constitute *bonna* for either river water or rainwater flooding. However, others believed that to be considered *bonna* the water level had to be sufficiently high to hamper daily life (20%), partially submerge crops (17%), inundate settlements (15%), or make roads impassable (13%) (Figure 5.14). 80% of farmers agreed that *barsha* flooding is beneficial because traditional cropping practices and local people are well adapted to the associated water levels. However, about 20% of farmers were of the opinion that it is *bonna* flooding that is most beneficial in promoting soil fertility even though it damages crops and disrupts people's lives. While farmers differed in their opinions of what constitutes *bonna* versus *barsha* flooding and the relative benefits of one versus the other, they all confirmed that they take into account the possibility of flood damage when deciding which crops and varieties to plant on the different kinds of land that they farm.

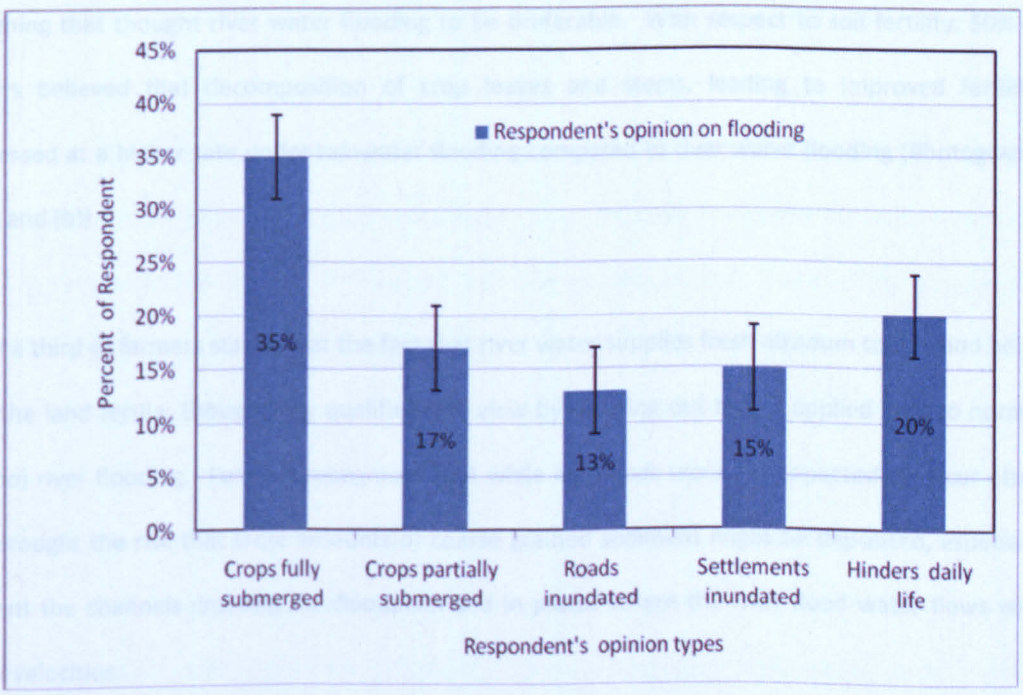


Figure 5.14 Respondent's opinions concerning the definition of extreme flooding (*barsha*)

The farmers were also particularly concerned about the type of sediments deposited by flooding. Based on their experience and long held beliefs, most farmers assume normal floods deposit a relatively thin layer of fine-grained sediment (silt), which is beneficial to agricultural cropping. They further believe that while extreme floods may deposit a thicker layer of fresh alluvium, they also bring the possibility that this might include coarse grained sediment (sand) that can damage the standing crop, decrease soil fertility and reduce their potential to cultivate the land during the post-monsoon season. Farmers expect and plan on flood levels usually being normal rather than extreme.

Table 5.9 presents the respondents' opinions on the value of river and rainwater flooding of agricultural land and their perceptions concerning the relative importance of different sources of soil fertility. Two thirds of respondents believed that rainwater flooding is better for agricultural crops than river water flooding. The major reasons given for this opinion were concern about the possible long duration of river water inundation and the possibility of sand deposition. The chances of crop inundation are higher with river flood than with rainwater flooding. As a result, crop damage tends to be greater and it hamper the daily life of the local people to a greater extent. Respondents who have experience of farming the land (current and retired land owning farmers, tenant farmers, and agricultural workers) mainly favoured rain water flooding and it was respondents not directly involved in farming that thought river water flooding to be preferable. With respect to soil fertility, 50% of farmers believed that decomposition of crop leaves and stems, leading to improved fertility, progressed at a higher rate under rainwater flooding compared to river water flooding (Photographs 5.7(a) and (b)).

About a third of farmers stated that the fact that river water supplies fresh alluvium to the land helps keep the land fertile, though they qualified this view by pointing out that it applied only to normal (*barsha*) river flooding. Farmers recognised that while big floods were not expected to occur often they brought the risk that large amounts of coarse grained sediment might be deposited, especially adjacent the channels crossing the floodplain and in places where the river flood water flows with higher velocities.

A smaller proportion of respondents (14%) rated the development of algal (*shaola)* mats, which are aggregates of green and blue algae as the main source of improved fertility arising from flooding. In English, these are termed Cyanobacteria with the class name Cyanophyceae. This type of algae does indeed make a contribution to soil fertility through nitrogen (N_2) fixation and in increasing the soils capacity to hold water (Catling, 1992; Brammer, 1995).

Table 5.9 Respondents' opinions concerning the relative merits of rainwater versus river water flooding and perceptions on the main source of improved soil fertility

Respondent types	Better type of flooding		Main source of soil fertility		
	Rainwater	River water	Crop decomposition	Algal mat	River water sediment
Farm own land	30	10	20	5	15
Employ people to farm	3	5	-	-	8
Rent land out to farm	7	3	5	3	2
Cash crop farmer	7	-	4	-	3
Tenant farmer pays money	-	2	-	-	2
Tenant farmer pays crops	1	2	2	1	-
Perennial farm worker	3	2	3	2	-
Seasonal farm worker	4	2	5	-	1
School teacher	2	2	2	1	1
Local administrator	2	2	2	1	1
Agricultural supervisor	-	1	-	-	1
Retired farmer	7	3	8	1	1
Total (%)	66	34	51	14	35
	100			100	

Field studies Algal (*shaola*) mats are plentiful in *aman* paddy and current fallow land (land used for cultivation in the pre-monsoon and crops harvested early monsoon and during monsoon temporary fallow) during monsoon seasons (Photograph 5.8) and volumes of algae present in selected paddy fields were measured as part of the field study (Table 5.10). The algal mats were collected from the 1-m^2 areas within the field during periods of flooding. These mats were dried out in the open air and the mass weight in grams (g) was measured. In 2007, the algal mats had densities of 70, 90 and 180g m^{-2} in fields devoted to deep-water *aman* paddy, shallow water paddy and current fallow land, respectively. The densities were higher in 2008, the equivalent figures being 120 g m^{-2}, 190 g m^{-2} and 350 g m^{-2}. The average density for all agricultural land was 113 g m^{-2} in 2007 and 220 g m^{-2} in 2008, indicating that the contribution of algal growth to soil fertility may have doubled in 2008 compared to

2007. Land use also appears to be a significant factor, with shallow water paddy producing more algae than deep-water paddy in both years, production being highest in land left fallow, perhaps due to the influence of agricultural practices on the depth and hydraulics of floodwaters.

The field evidence also suggests that greater abundance of algae in paddy fields is restricted to areas inundated by rainwater flooding. This probably reflects the fact that rain-fed flood water is clearer and transmits light deeper than turbid river water and that, consequently, rates of photosynthesis, organic matter growth and decomposition are higher (Photograph 5.9).

Table 5.10 Spatial distributions of algae (cyanobateria) measured in 2007 and 2008

Fields	Scientific name	Mass of algae (g m^{-2})	
		2007	2008
Deep water rice *(Vasha Aman)*	*Oryza sativa Linn.* (Gramineae)	70	120
Shallow water rice *(Digha Aman)*	*Oryza sativa Linn.* (Gramineae)	90	190
Fallow fields (current fallow)		180	350
Average		113	220
Standard deviation		59	118
Percent (%)		34	66
Variation		-	32%

However, the results of the survey show that relatively few farmers are actually aware of the potential benefits of algal mats. Due to this lack of awareness, the majority of farmers clear these mats from their fields, restricting their extent to the plot boundaries (*iale*). In fact, many farmers believe algae to be weeds that are harmful to agricultural crops. Conversely, just 5 of the 40 farmers interviewed were fully aware of the importance of algae to soil fertility. These farmers reported that they routinely break up mats and mix the algae with the soil through ploughing it into the land as a green manure, with the specific purpose of increasing soil fertility. Their opinions and practices support the view of Brammer, who extolled the virtues of algae in increasing organic matter content and soil fertility as long ago as 1995.

(a) Rainwater flooding

(b) River water flooding

Photograph 5.7 (a) Rainwater flooding with floating crop leaves and stems that are decomposing rapidly to increase soil fertility by adding organic matter; **(b)** River water flood sediments improve soil fertility in normal years but allow little light penetration and produce less organic matter

(a) Algal mat (cyanobacteria) in deep-water paddy field

(b) Algal mat (cyanobacteria) in shallow water paddy field

(c) Algae (cyanobacteria) mat in a currently fallow area of agricultural land

Photograph 5.8 (a), (b) and (c) Examples of blue-green algae (cyanobateria) observed in the field survey.

Photograph 5.9 Clear, rainwater flooding allows faster photosynthesis, plant decomposition and algal productivity, adding to soil fertility

Despite this, and although a few in-depth studies have been performed by the International Rice Research Institute (IRRI) (Roger and Kulasooriya, 1980; Catling, 1992), the fundamental importance of algae to soil fertility and agricultural crop productivity in the floodplains of Bangladesh remains largely unrecognised.

The results of the field study reported only the quantities of algal mats in deep and shallow water paddy field and current fallow land. It is much more abundant in clear water, where is inundated by rainwater. Because the growth of the algal mats are much more related with the water turbidity. The river water flooding area is more turbid than the rainwater flooding; hence, fewer quantities of algal mats grow in the river flooding area.

The International Rice Research Institute (IRRI) used the acetylene reduction technique to establish the level of nitrogen fixation by the blue-green algae growing in paddy fields, finding an average contribution of 30 kg ha-1 of nitrogen per crop season (Roger and Kulasooriya, 1980; Brammer, 1995b). Rother *et al.* (1988) and Catling (1993) used a similar technique in deep water paddy areas in Bangladesh (including parts of the Jamuna floodplain) to generate annual figures of 8-18 kg ha-1 for nitrogen fixation, which is equivalent to 13-30 kg ha-1 of urea, the nitrogenous fertilizer usually applied in Bangladesh (ISPAN, 1995). Roger and Kulasooriya (1980) pointed out that estimation of nitrogen–fixing activity based on analysis of gas changes in an enclosed atmosphere is an insensitive method that has rarely been used, while the acetylene reduction technique is presently the most widely used, because of its simplicity, rapidity, and sensitivity. However, literature describing the application the acetylene reduction technique as an means of estimating nitrogen input to estimate the C/N ratio of the dry algal mat is limited. This, therefore, limits the possibility of using the carbon-nitrogen ratio to measure the nitrogen-fixing rate. In light of this, my study was restricted to investigation of the spatial distribution of the blue green algae rather than its bio-chemical analysis.

The preliminary findings of the field study of algal growth and perception of local farmers on soil fertility support the proposal of Brammer (1995) that further, in-depth research should be performed on the physio-chemical and biological properties of algal mats and verify their role in contributing to soil fertility. The results of the questionnaire and interview survey suggest that vernacular knowledge of the benefits of algal mats is restricted amongst farmers and that current agricultural practices generally reduce the effectiveness of these mats in naturally fertilising the soil and reducing dependence on artificial fertilisers.

5.4 Conclusion

These results suggest that vegetation (sun grass) and agricultural crops growing in a given plot of land influences the quantity, calibre and grading of the sediment trapped during the monsoon season. It follows that decisions made concerning whether to plant, for example, deep or shallow water paddy in a plot close to a channel spilling water on to the floodplain will affect both the characteristics of sediment filtered out of the flood water and sedimentation in plots further away, in ways that are important for both soil fertility and agricultural productivity.

Field evidences have established that farmers are deeply concerned about the risk that an extreme monsoon event will deposit copious amounts of flood borne sand on their land, rendering it unsuitable for cropping and requiring that it be left fallow during the post-monsoon and following pre-monsoon and monsoon seasons. As a way of reducing this risk, they often cultivate crops that can be harvested prior to the flood season, with much of the land along the channels crossing the floodplain being left fallow actually during the monsoon flood. As a result, floodwaters are able to flow across the land with little sediment trapping, with the outcome that the spatial extent of coarse grain deposition is greater than would be the case in land near the channel had been cultivated. It follows that the results of the sedimentation study could be used to guide farmers towards the use of buffer plots of selected crops, such as shallow water paddy, along watercourses to protect the remainder of their land from deposition of coarse-grained sediment. The next chapter details of agricultural land use and vegetation dynamics due to sedimentation.

CHAPTER 6 AGRICULTURAL LAND USE AND VEGETATION DYNAMICS

6.1 Introduction

This chapter presents the results of field investigation on agricultural land use and vegetation dynamics on the active and young floodplain of the Brahmaputra-Jamuna River during the pre-monsoon, monsoon and post-monsoon seasons in 2007 and 2008. The earlier sections provide a number of important insights concerning how floodplain sedimentation varies with floodplain topography (chapter 4) and how it interacts with agricultural crops and vegetation (chapter5) and this section details the spatial and temporal variation of the agricultural land use and vegetation quantitatively. The exploratory statistical analysis is employed to investigate the dynamics of agricultural land use and vegetation type.

6.2 Methods of data collection

The data related to agricultural land use and vegetation was collected in six separate phases in 2007 and 2008 following the field survey, both informal and formal discussion with local farmers. The first (pre-flood) phase included field reconnaissance to become familiar with the floodplain environment and select suitable sites at which to investigate land use and vegetation, where process measurements would be made. The land use and vegetation survey conducted in pre-monsoon in 2007. The second (flood) phase centred on vegetation sampling and checklist of existing agricultural land use. The third (post-flood) phase consisted of a post-flood field survey of vegetation and land-use. This was particularly important following the large flood in 2007. Fieldwork in 2008 also adopted these procedures, again within a three-phase sequence of works. The subsequent sections describe the rationale of the field survey techniques and procedure of the land use and vegetation information collection.

6.2.1 Plot level land use survey

In the early 1990s, several classic methods were developed for macro scale land use surveys. Such as, traverse and generalised reconnaissance methods (Hilgendorf, 1935; Madden, 1940; and

Cumberland, 1941). In the UK during the 1930s, Dudley Stamp performed a notable, systematic land use survey using observation and fieldwork to support formulation of national policy on land use planning and development (Stamp, 1943). These methods all rely on rapid reconnaissance to facilitate a detailed field-by-field survey. However, application of these techniques was limited by lack of accuracy, time, and cost. To address these limitations, Hudson (1936) developed the 'unit area method'. This was further developed by the Tennessee Valley Authority (T.V.A) of the United States National Resources Planning Board, who devised a 'unit area land classification method' and applied it to over 106,190 km^2 of the Tennessee River drainage basin for large scale. In this method, both the physical and human landscapes are investigated, with the results digitised and tabulated. The data are expressed in terms of 'complex fractional code'. The denominator and numerator of the fractional code contain the physical characteristics and information concerning the use of land, respectively.

Nowadays, a range of techniques is used for land use surveys, depending on the scale of the survey area, the ease of field survey and the availability of remotely sensed imagery with a suitable resolution. For large areas, any remote sensing images are useful, but only very high-resolution imagery is worthwhile for micro-scale surveys. When lands use varies seasonally, further issues arise with the temporal resolution of remotely sensed images. In the present study area, the individual plots are very small and field surveying is still essential for capturing the information at the plot level. In addition, land use varies between the pre-monsoon, monsoon and post-monsoon seasons, which mean that remotely-sensed imagery of sufficiently high resolution, are unavailable at the required frequency.

Therefore, the land use survey was performed through fieldwork consisting of base map preparation, reconnaissance, land use indexing, and field survey through observation, in conjunction with identifying and interviewing key informants to check and validate the findings.

6.2.1.1 Base map preparation

The preparation of a suitable base map is a very important part of land survey research. In Bangladesh, a range of maps with the potential for use as a base map is available (Table 6.1). Among these, the large-scale (1:3,960) *Mauza*(village) map is used in Bangladesh to aid village revenue collection according to the land unit, which is known as a cadastral map. It provides detailed boundary information for land plots as well as point features (mosques, ponds) and linear elements (roads, stream) that are very useful in the field when identifying villages and individual plots. Therefore, the *Mauza* map was selected as the base map for land use surveying and mapping (Figure 6.1).

Table 6.1 Summary information of maps available for field studies in Bangladesh

No	Common name:	Full title of map	Scale	Organization
1	*Mauza* map (Cadastral map) (1970-81)	Boro Bania *Mauza* under Daulatpur *Upazila* (RS#1835,JL#52, Sheet,1and2)	16"= 1 mile 1: 3,960	Settlement Office, Survey of Bangladesh (SOB)
2	*Topo*-sheet (1963)	Topographic Map -1st edition (Mainly Index no. 78 H/9, 79 H/12, 79 H/13 and 79 H/16	1"=0.789 mile 1: 50,000	Survey of Bangladesh (SOB)
3	*Upazila* Map (1994)	*Daulatpur* Thana, District: Manikgong	1:50,000	Local Government Engineering Department (LGED) and UNDP
4	Soil Map (1992)	Soil and land type map, *Daulatpur* Thana	1;50,000	Soil Resources Development Institute (SRDI), Dhaka
5	District Map (1958)	District Dacca (administrative map of greater Dhaka)	1:253,440	Bengal drawing office
6	BBS Atlas (1985)	*Mauza* of Manikgaonj District, Small area atlas	1:200,000	Bangladesh Bureau of Statistics under Ministry of planning

6.2.1.2 Collection of detailed plot level land use information

Reconnaissance of the study area was undertaken in May 2007. This included initial observation and classification of existing land uses and discussion with local people regarding the nature of flooding in their part of the study area (*Boinna, Barsha*, river flow and rain fed flood), and seasonal cropping patterns.

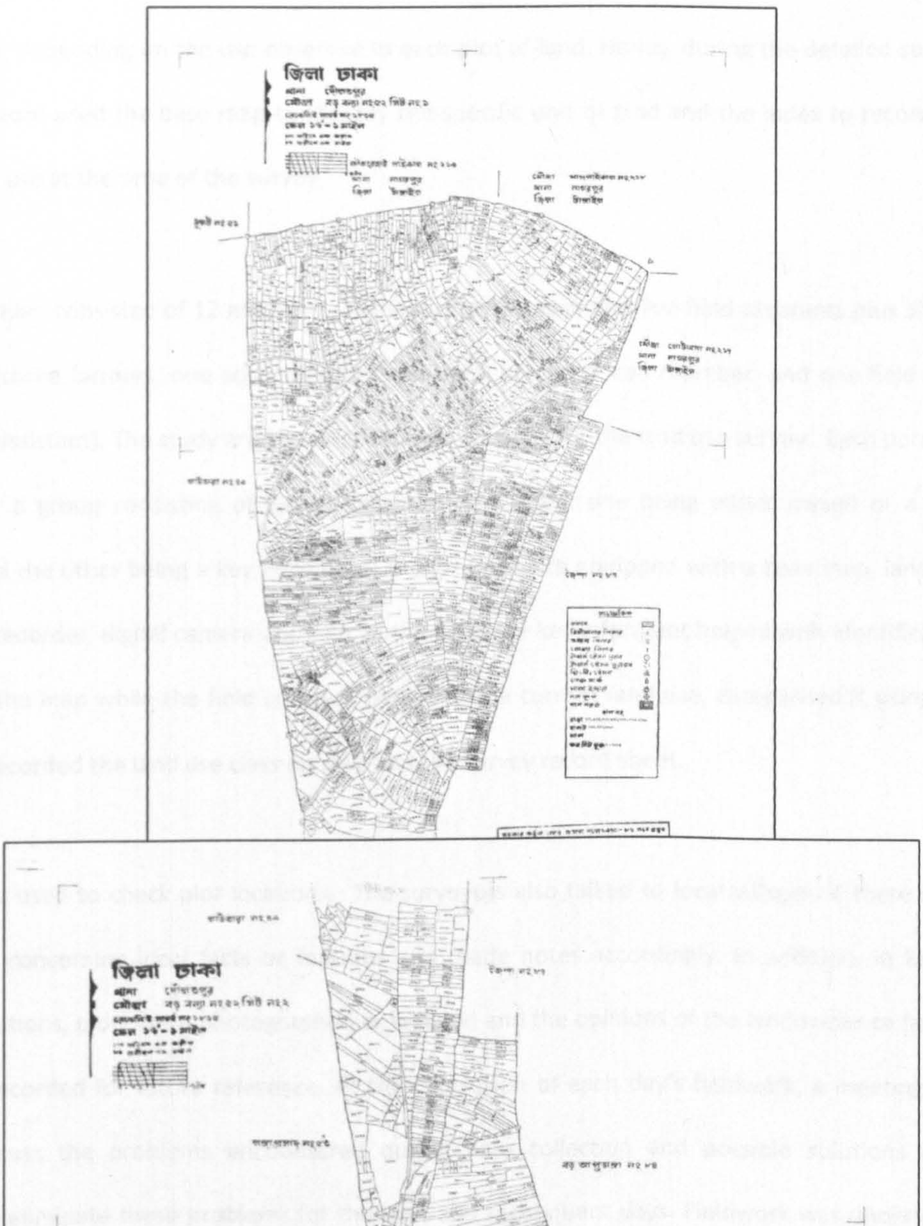


Figure 6.1 Base map of the study area based on the *Mouza* map (Plot level cadastral map)

An index of land uses was prepared to categorise plot level information, based on the existing land use types observed in the reconnaissance survey (Appendix-B). The index comprises of 10 broad and 32 sub-categories, with numerical indexing so that surveyors could easily place a tick mark (√) in the relevant box, depending on the use observed in each plot of land. Hence, during the detailed survey, the survey team used the base map to identify the specific unit of land and the index to record the current land use at the time of the survey.

The survey team consisted of 12 members. These included myself and five field assistants plus six key informants (three farmers, one schoolteacher, one local union parisad member, and one field level agricultural assistant). The study area was divided into six parts for the land use survey. Each part was surveyed by a group consisting of two members of the team; one being either myself or a field assistant and the other being a key informant. The groups were equipped with a base map, land use index, tape recorder, digital camera and GPS. In the field, the key informant helped with identification of plots on the map while the field surveyor observed the current land use, categorised it using the index, and recorded the land use class on map and the survey record sheet.

The GPS was used to check plot locations. The surveyors also talked to local villagers if there were any queries concerning local facts or features and made notes accordingly. In addition, in key or complex locations, plots were photographed or videoed and the opinions of the landowner or farmer were tape-recorded for future reference. At the conclusion of each day's fieldwork, a meeting was held to discuss the problems encountered during data collection and possible solutions were identified to eliminate these problems for the next and subsequent days. Fieldwork was undertaken in this manner during six phases, corresponding to the pre-monsoon, monsoon and post monsoon periods of 2007 and 2008.

6.2.1.3 Development of land use GIS database

Development of the GIS database involved the creation of a database in Microsoft Excel 2003 and an ArcView 3.3 project, which included a polygon feature theme of the base map. A query was created in the Microsoft Excel 2003 database of the data required for spatial analysis and linked to the ArcView 3.3 project. The collected land use information was reviewed, entities and attributes were identified, each of the attributes was classified and coded, and the data added to the Microsoft Excel dataset for query creation. Each column contained a specific variable of land use type. After adding the land use information against the relevant plot ID, the file was saved in a dbase (database) file format.

The base map was digitized and a shape file prepared using Arc view GIS. This included a total of 2330 plots as polygon features. Each of the polygons was linked to the theme table and, using the query builder, the features were identified for specific field information. Next, the dbase file was added to the shape file (with common plot ID's) using the join button in the attribute table menu of Arcview GIS, to produce the GIS database (Figure 6.2). In this way, an attribute table was developed to analyse spatial variation in plot level land use. After each of the seasonal field surveys, attribute tables were developed following the same methodology and the season-wise data were added to support temporal analysis.

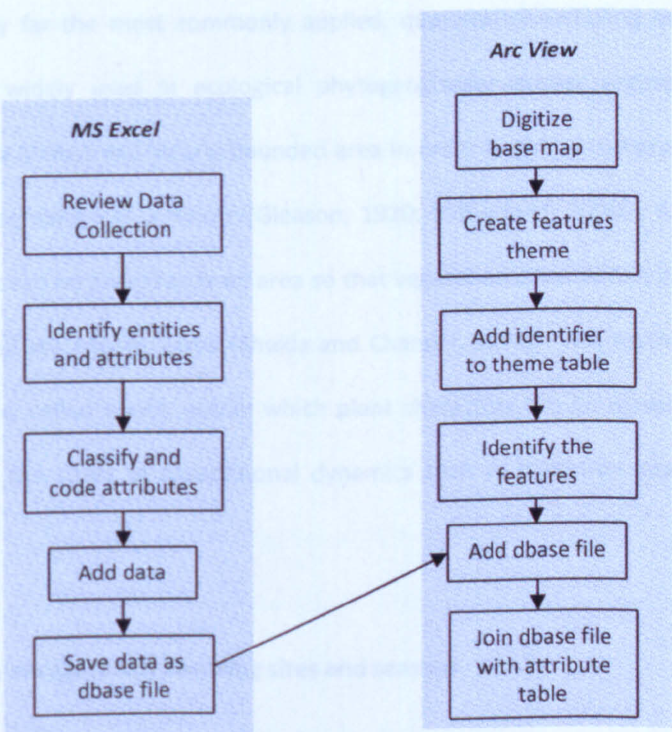


Figure 6.2 Summary of the initial GIS database development procedure of land use

6.2.2 Field survey of vegetation types

Biologists, plant ecologists and environmental scientists use a range of qualitative and quantitative methods to study vegetation communities. Commonly applied approaches involve investigating the structure of plant communities through analysis of their floristic composition or species content, together with studies of stratification, life form, sociability and inter-specific associations. Experienced researchers, who need to define a plant community quickly and simply, based on their expert observations, mostly use qualitative methods. Conversely, studying the sociological order of a plant community requires quantitative measurements of each individual of plant species to establish their density, frequency and abundance. In practice, it is impossible to count the actual number of plant species in a particular habitat. Therefore, researchers must estimate the species content in a habitat by sampling at selected locations with the study area. Several methods have been developed to quantify the species content within a particular habitat, including Quadrats, transects, loop and point sampling. Selection of the appropriate sampling method depends on the objective of the study.

The oldest and by far the most commonly applied, quantitative sampling method is the quadrat survey, which is widely used in ecological phytogeography studies vegetation or environment conditions within a limited and clearly bounded area in order to gain a comprehensive knowledge of the vegetation assemblage as a whole (Gleason, 1920; Sutherland, 2006). A quadrat is a square-shaped frame that can be placed over an area so that vegetation cover within it can be identified, the plants counted and the species listed (Shukla and Chandel, 1991). This method allows the user to define a fixed area, called a plot, within which plant characters can be measured. It also plays an important role in the study of associational dynamics such as migration and succession of plants species.

6.2.2.1 Selection of vegetation sampling sites and seasons

The vegetation survey covered the variety of shrub and tree species found in natural areas and homestead forests. The type and diversity of vegetation varies with the landform characteristics of the floodplain. Recognising this, stratified sampling was used to distribute study sites between the natural levee, back slope and back swamp landform areas. Within the landform areas, a random sampling technique was employed to distribute sample quadrats. As flooding is the main determinant of temporal variability in the floodplain environment, the timing of vegetation sampling was selected to reflect of the annual cycle of flooding. Sample episodes therefore coincided with the; pre-monsoon (before June), monsoon (June to September) and post-monsoon periods (October to December), in 2007 and 2008. Hence, in all, six quadrat surveys were conducted to record vegetation species present at the selected sites.

6.2.2.2 Quadrat size determination

Quadrat sampling attempts to define plant community characteristics for an area much larger than the actual area sampled. Consequently, care must be taken to obtain samples that represent the entire habitat while eliminating operator bias during fieldwork. Quadrat size was determined on the basis of Cain's technique, using a 'species-area curve' (Cain, 1938). The 'species-area' curve presents the relationship between areas size and the number of species found in an area of a given size. It provides the information necessary to select the minimum number and size of quadrats necessary to provide an adequate sample of a given vegetation community. The curve was developed using the results of a pre-investigation of the vegetation communities encountered within the different floodplain landforms. The curve was then used to define the minimum area within which the maximum number of species of each vegetation type could be found and then that minimum 'space-size' was selected as the quadrat size for that particular type of vegetation(Figure 6.3).

The curve shows that smaller plants require smaller quadrats to capture the maximum species diversity. This is due to the higher densities at which the plants grow. Numerous studies have evaluated quadrat size, and, though no universal recommendations have emerged (Krebs, 1999 and Sutherland, 2006), the sizes most often used are listed in Table 6.2.

Considering the 'species-area' curve and the general guidance above, a quadrat frame of 2m by 2m was selected for sampling herbs, aquatic macrophytes (including Blue green algae) and short shrubs. 5m × 5m, taped quadrats were selected for tall shrubs (Sun grass) and 30m × 30m taped quadrats were used for homestead forests and natural trees (Figure 6.4).

Table 6.2 Generally recommended quadrat sizes for vegetation surveys

Quadrat size (m^2)	Vegetation type
0.01-0.25	• Bryophyte • Lichens and • Algae
0.25-16	• Grassland • Tall herb and short shrub • Aquatic macrophyte
25-100	• Tall shrub community
400-2500	• Trees

6.2.2.3 Vegetation information recording

The earlier section explain the land use survey, which includes only the land being used for agricultural crops. Although agricultural crops are vegetation but this study mainly covers the naturally grown vegetation rather than the cultivated crops. Vegetation sampling proved time consuming and in the event, sampling was limited to a total of 20 quadrats, with 5 quadrats being deployed randomly to sample vegetation in areas of (1) Herbs, (2) aquatic vegetation and short shrubs, (3) tall shrubs and (4) trees. The number of species, plant names (including native names), habits, collection number, collection area, location (latitude, longitude), were recorded in the field and any contextual information was written in a field notebook.

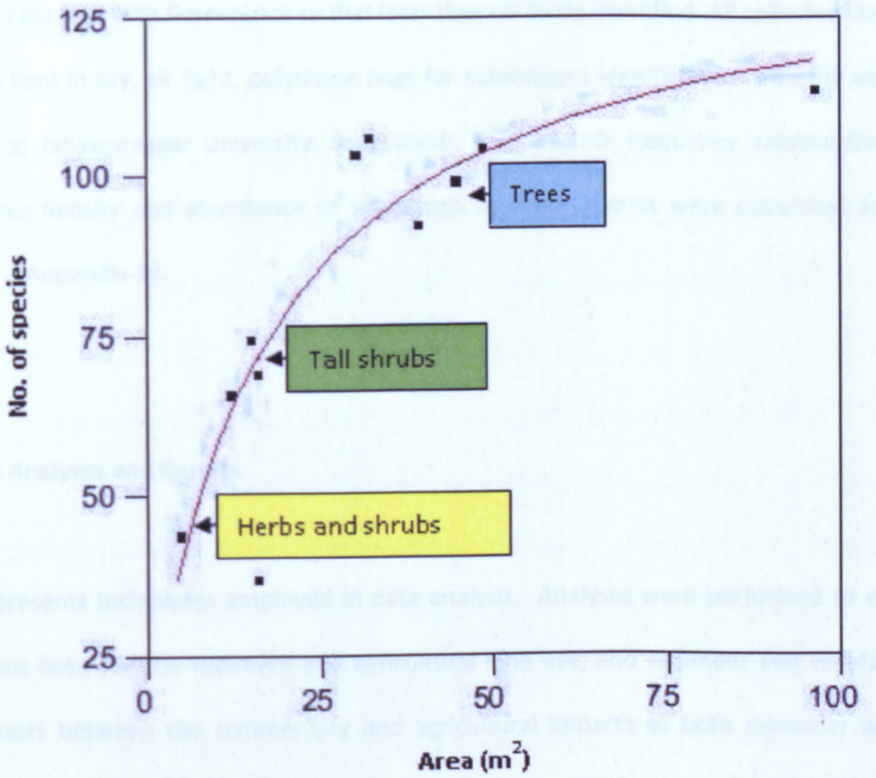


Figure 6.3 Species-area curves used to determine the minimum required quadrat size (Modified after Cain, 1938)

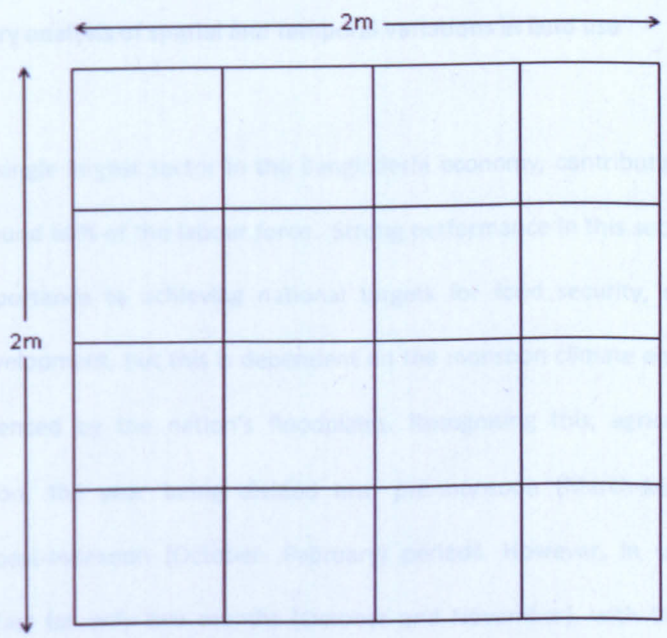


Figure 6.4 Quadrat frame made of wood and string used in areas populated by small plants during the field survey of vegetation.

Rare samples were collected in larger numbers than the more common species and most of the samples were collected with florescence so that later they could be identified. All collected vegetation samples were kept in dry, air tight, polythene bags for subsequent identification with the assistance of a botanist at Jahangirnagar University, Bangladesh. The absolute frequency, relative frequency, density, relative density and abundance of vegetation in each quadrat were calculated according procedures (Appendix-D).

6.3 Data Analyses and Results

This section presents techniques employed in data analysis. Analyses were performed to elucidate the interactions between the sediment and agricultural land use, and sediment and vegetation, as well as contrasts between the sedimentary and agricultural impacts of both rainwater and river flooding. The approach employed Exploratory Data Analysis (EDA), coupled with bivariate and geostatistical techniques, performed within Arc-GIS (version 9.2).

6.3.1 Exploratory analysis of spatial and temporal variations in land use

Agriculture is the single largest sector in the Bangladeshi economy, contributing about 30% of GDP and employing around 60% of the labour force. Strong performance in this sector of the economy is of paramount importance to achieving national targets for food security, employment, poverty alleviation and development, but this is dependent on the monsoon climate and seasonal pattern of inundation experienced by the nation's floodplains. Recognising this, agricultural land use was analysed by season, the year being divided into pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October- February) periods. However, in some years the post-monsoon season last for only two months (October and November), with December to February treated as the dry season (Brammer, 2002).

6.3.1.1 Land holdings size and types

The developed land in the study area is made up of agricultural land, settlements and roads, with undeveloped land occupying the beds of distributary Rivers and seasonally flooded areas of *beels*. Settlements are concentrated on flood free high land, usually on the natural levee or the floodplain ridges separating lower-lying flood basins (Brammer, 2002). The average land holding in Bangladesh is only 1 hectare (BBS, 2001), and even these small holdings are often divided into ten or more sub-plots due to sharing of inherited land between siblings. The Bangladesh Bureau of Statistics (BBS, 2006) recognizes four classes of farmer based on their land holding (plot) size: large (≥ 3ha, 4%), medium (1-3ha, 18%), small (0.02-1ha, 51%) and land less (≤0.02ha, 27%). More recently, Kamruzzaman and Takeya (2008) found about 80% of farmers to be land less (≤0.20ha), marginal (0.20ha to ≤ 0.4ha) and small (0.40ha to ≤1.0ha) and 20% of farmers are large farms holder. The 2,330 land holdings within the study area reflect this national picture, ranging in size from 0.01 to 2.22 ha, and with an average size of 1.11 ha. Most plots (>60%) are very small (0.01 to 0.05 hectares), while only 50 are in the 'large farm' category (>2.22 ha) (Figure 6.5). Details land holding size (farm size) is described in chapter 6 section 6.6.2 in relation to the agricultural land use.

Land type in the study area was divided into seven classes, based on the depth of flooding (Table 6.3 and Figure 6.6). These land types are comparable to those used in the national Agro-Ecological Zones (AEZ) classification system.

Table 6.3 Land types in the study area. Land types are comparable to those used in the classification of Agro-Ecological Zones (AEZ) for Bangladesh (see Table 6.4).

Land type (AEZ)	Area 2007 (ha)	Area 2008 (ha)	Average	Average %	Variation	Variation%
High land (H)	48	65	57	21	17	12
Medium high land (MH)-1	17	71	44	16	54	38
Medium high land (MH)-2	186	116	151	55	-70	-50
Medium low land (ML)	8	8	8	3	0	0
Low land (L)	4	4	4	1	0	0
Very low land (VL)	9	9	9	3	0	0
Bottomland (BL)	2	2	2	1	0	0

Table 6.4 Land types based on flooding depth according to the Agro-ecological zone

Land type (AEZ Classification)	Normal maximum flood depth (cm)	MPO Classification
High land (H)	0	F0
Medium high land (MH)-1	0-30	F0
Medium high land (MH)-2	30-90	F1
Medium low land (ML)	90-180	F2
Low land (L)	180-300 (flooded < 9 months) 180-300 (flooded > 9 months)	F3 F4
Very low land (VL)	>300	F4
Bottomland	Mainly >300, but includes perennially wet.	F4

Note: This classification was developed on the basis of the country's reconnaissance soil surveys (FAO, 1988). The Master Plan Organization (MPO, 1987) adopted the system with some modifications.

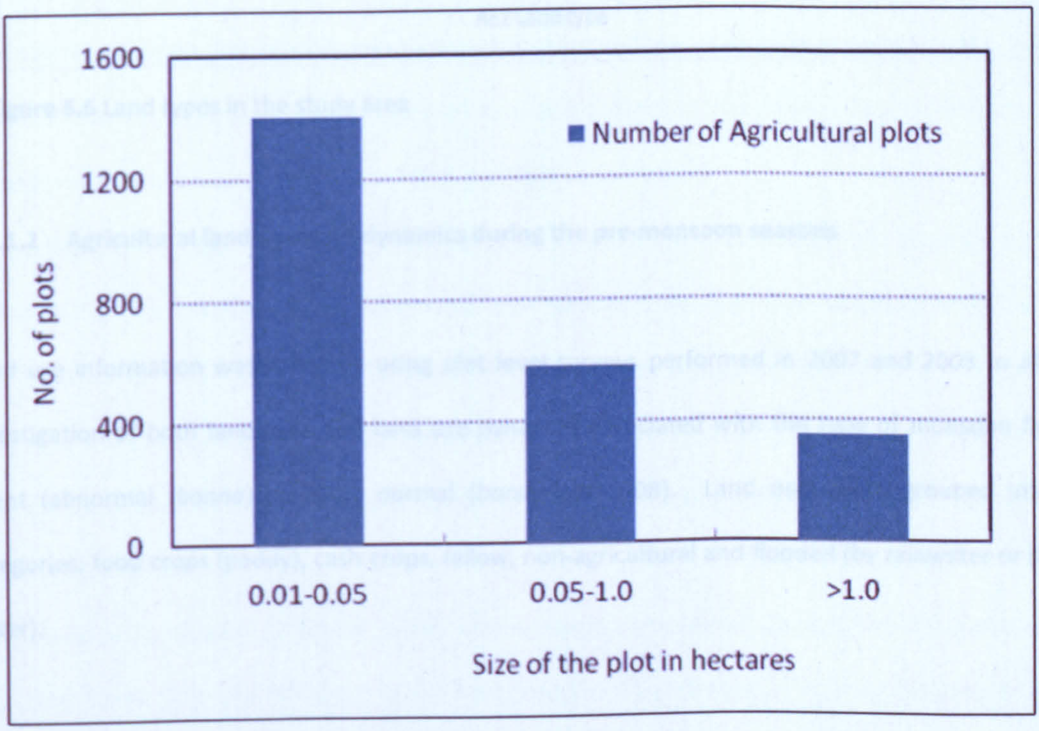


Figure 6. 5 Variation of the agricultural holding sizes in the study site

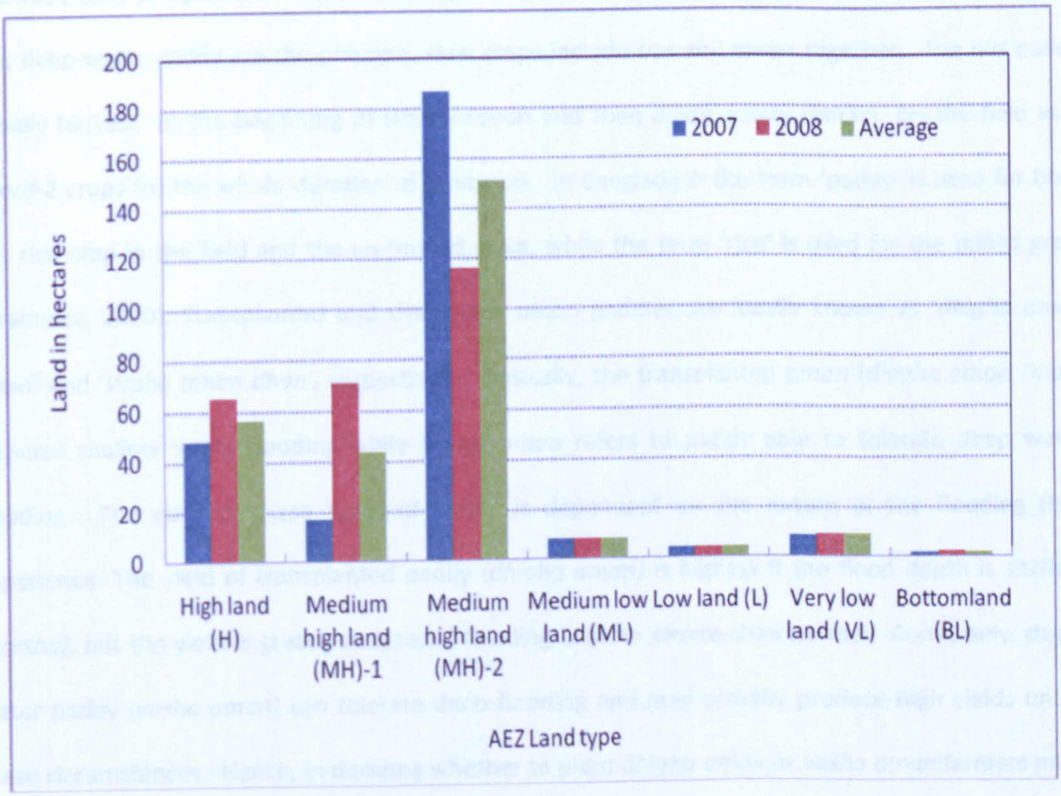


Figure 6.6 Land types in the study area

6.3.1.2 Agricultural land uses and dynamics during the pre-monsoon seasons

Land use information was collected using plot level surveys performed in 2007 and 2008 to allow investigation of both land uses and land use dynamics associated with the type of monsoon flood event (abnormal (*bonna*) in 2007; normal (*barsha)* in 2008). Land uses were grouped into 5 categories; food crops (paddy), cash crops, fallow, non-agricultural and flooded (by rainwater or river water).

Two main cropping seasons are recognized in Bangladesh: *kharif and rabi*. The *kharif* season is sub-divided into *kharif-1* and *kharif-2*. The *kharif-1 season* comprises the pre-monsoon period and the first half of the monsoon period. The *kharif-2* season includes the second half of the monsoon and the early post-monsoon periods (Brammer, 2002).

The *aus* paddy and jute are the principal single crops of *kharif-1* season and transplanted *aman* paddy and deep-water paddy are the principal, dual crops include *aus* and *aman* together. The *aus* paddy usually harvest at the beginning of the monsoon and then *aman* paddy remain on the field as a *kharif-2* crops for the whole duration of monsoon. In Bangladesh the term 'paddy' is used for both the rice crop in the field and the un-husked grain, while the term 'rice' is used for the milled grain (Brammer, 2000). Transplanted and deepwater *aman* paddies are locally known as *'dhigha aman Dhan'* and *'Vasha aman dhan'*, respectively. Basically, the transplanted *aman* (*dhigha aman Dhan*) requires shallow water flooding while *Vasha aman* refers to paddy able to tolerate deep water flooding. The yield of these types of paddy is dependent on the nature of the flooding they experience. The yield of transplanted paddy (*dhigha aman)* is highest if the flood depth is shallow (*Barsha),* but the yield is greatly reduced if flooding is more severe than normal. Conversely, deep-water paddy (*vasha aman*) can tolerate deep flooding and may actually produce high yields under these circumstances. Hence, in deciding whether to plant *dhigha aman* or *vasha aman* farmers must try to anticipate whether a normal (*barsha*) or extreme flood is the more likely. It follows that agricultural land use in the study area is dynamic (Table 6.5 and 6.6).

During the pre-monsoon seasons of 2007 and 2008, land use was divided into four main types. The first is 'agricultural', which may be sub-divided into food and cash crops. Food crops comprise: single paddy (1. *aus*, 2. transplanted (*dhigha aman)* and 3. deep-water (*vasha aman)* paddy); and multiple paddy (4. mixed *aus* and *dhigha,* and 5. mixed *aus* and *vahsa aman* paddy). Hence, the three types of paddy were divided into five land use categories. Cash crops include jute, sugarcane, sesame, and sesbania (*dhanchya*).

The second land use class is 'fallow', which is land that is not currently being farmed due to recent sand deposition. This type of land is mainly found on the natural levee. The third category is 'non-agricultural', which comprises mainly of settlements and roads. The fourth category is 'water bodies', which include permanently inundated areas, such as perennially flowing distributaries of the Jamuna River and low lying areas that are always wet or water logged. It also seasonally inundated areas, such as local drainage channels (*khals*), which flow only during monsoon, and depressions that are flooded by river or rainwater for more than half the year. Little change was observed in the areas classed as 'non-agricultural' and 'water bodies'. There was, however, high variability in the areas classed as 'agricultural' and 'fallow'. The spatial distribution of agricultural land use dynamics was considered in relation to the landform units making up the floodplain in the study area.

On the natural levee, 35 hectares were used for *kharif* paddy (single *vasha* and *dhigha aman,* and mixed *aus* and *dhigha aman* paddy) cultivation in 2007, falling to only 18 hectares in 2008, which represents a large reduction of over 60% (Figure 6.7). No jute was cultivated in 2007, but this crop occupied 7 hectares (16%) of the natural levee in 2008. It was observed in the field that the land used to grow jute in 2008 had been used for paddy or sun grass strips in 2007. 3 hectares of sugarcane were observed in 2007, but this crop was absent in 2008. The area of sesame croplands was almost double changed (6 hectares in 2007 and 13 hectares in 2008. 5 hectares of the land that was used for paddy in 2007 was converted to *sesbania (dhanchya),* which took up 11% of the natural levee in 2008. This is significant as this crop is grown to restore soil fertility following deposition of coarse sediment. None of the land was fallow in 2007, but about 11 hectares (25%) fell into this category in the pre-monsoon period of 2008. This is further evidence of the effect of sand deposition associated with the 2007 monsoon flood, which would have reduced soil fertility and suitability for paddy or cash crop cultivation in the affected areas.

Agricultural land use dynamics and crop types in the back slope land unit differed from those on the natural levee. In 2007, the observed uses were paddy 116 hectares (83%), jute 14 hectares (10%) and sugarcane 10 hectares (7%). In 2008, paddy cultivation increased to 125 hectares (89%) at the expense of sugarcane, while jute area was almost unchanged (Figure 6.8). Within the paddy area, in 2007, single (*aus,* transplanted *aman* and *dhigha aman)* and mixed (*aus* and *dhigha aman, aus* and *vasha aman)* fields occupied 66 and 50 hectares, respectively. However, in 2008, the area of single paddy decreased to zero, with mixed paddy being preferred throughout.

Back swamps (*beels*) are seasonally flooded areas that are inundated for more than half year, even when the intensity of monsoon flooding is less than normal. Agriculture is absent from the 2 hectares of the back swamp that are perennially inundated, though aquaculture and capture fisheries are important here. In 2008 no agriculture took place in a further 3 ha of land that was water logged by heavy rainfall during the pre-monsoon period. In 2007, no rain-fed water logging occurred because the entire land unit was inundated by river water (Figure 6.9).

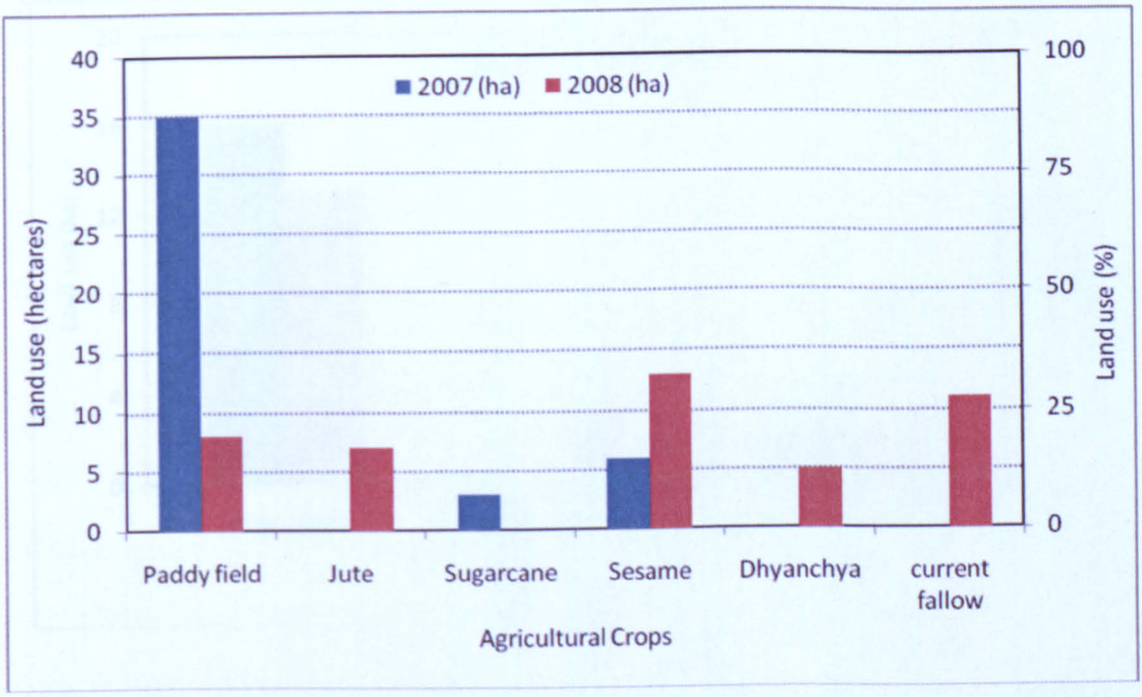


Figure 6.7 Dynamics of agricultural land use on the natural levee during the pre-monsoon seasons of 2007 and 2008

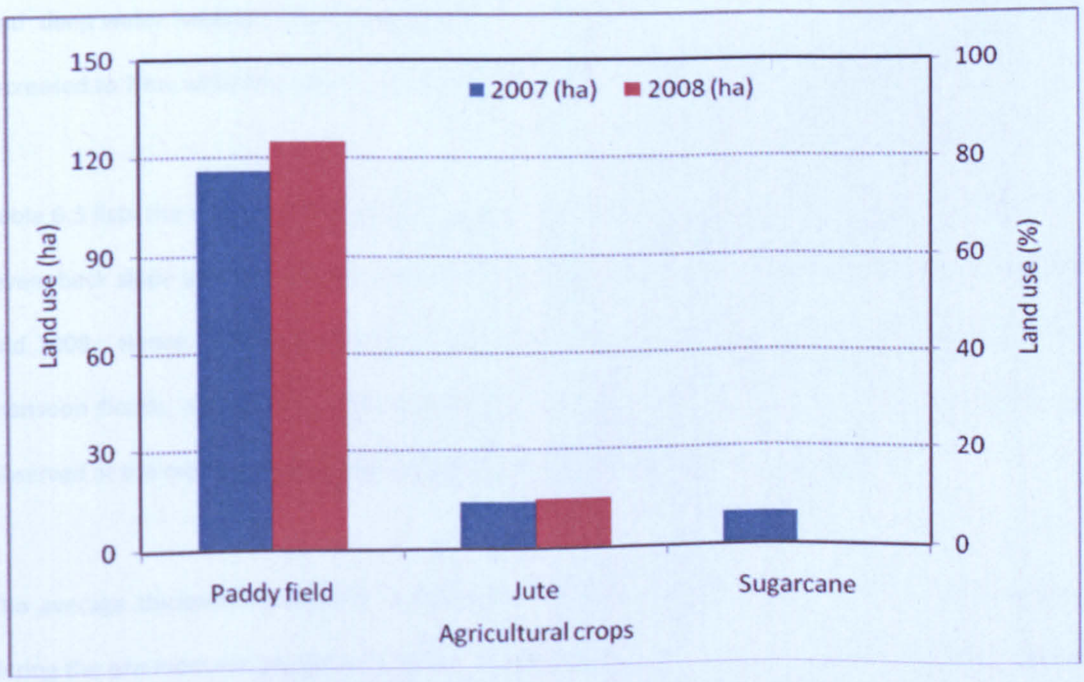


Figure 6.8 Dynamics of agricultural land use in the back slope land unit during the pre-monsoon season periods of 2007 and 2008

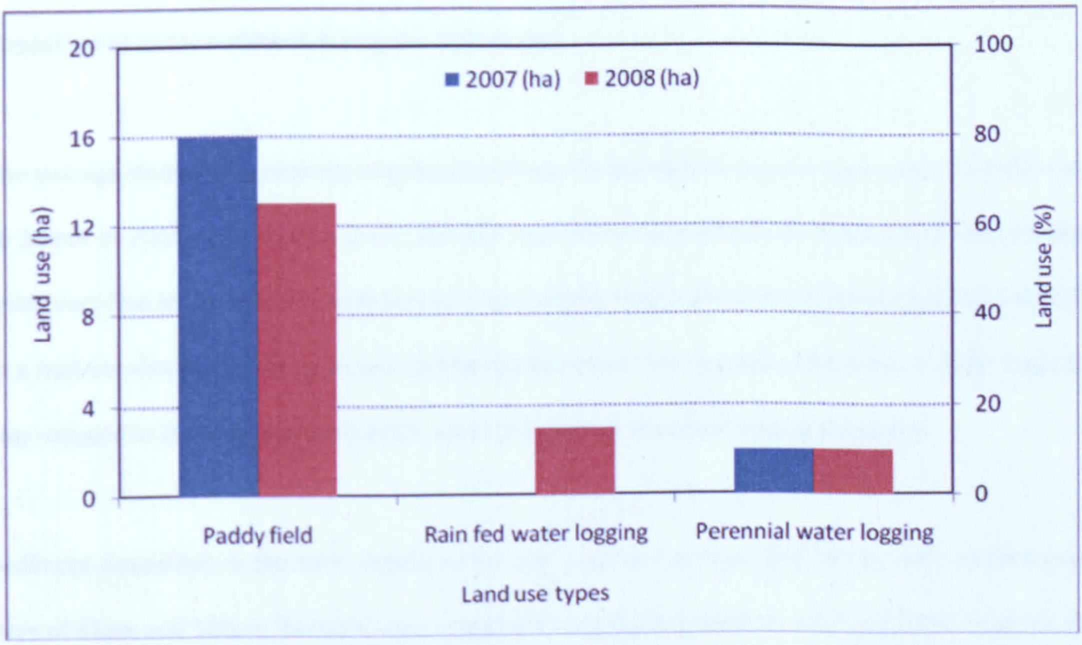


Figure 6.9 Dynamics of agricultural land use in the back swamp land unit during the pre-monsoon season periods of 2007 and 2008

Only 6 and 10 ha of land were used for single crop, deep water *aman* paddy and mixed paddy (*aus* and deep water (*vasha) aman*), respectively. In 2008, the single paddy of deep water *vahsa aman* increased to 7 ha, while the area of mixed *aus* and *vahsa aman* decreased to only 6 ha.

Table 6.5 lists the characteristics of deposited sediment measured at monitoring sites in the natural levee, back slope and back swamp units of the study area during the pre-monsoon seasons of 2007 and 2008. Hence, the observations correspond to sediment deposited during the 2006 and 2007 monsoon floods, respectively. The representativeness of the sediment thicknesses and properties observed at the monitoring sites was validated through discussion with local farmers.

The average thickness of recently accumulated, surface sediment observed on the natural levee during the pre-monsoon period was 55mm in 2007, and 20mm in 2008. The corresponding median grain sizes were 210µm and 350µm. These data indicate abundant deposition of fine to medium sand on the natural levee, especially following the catastrophic flood of 2007. The land use survey revealed that agricultural land use diversity was reduced in 2008, as a result of the widespread deposition of sandy sediment during the 2007 flood.

The average thickness of recently deposited sediment in the back slope area was 15mm in 2007 rising to 35mm in 2008, with median grain size also increasing from 105μm to 220μm (soil textural class being very fine to fine sand). The diversity of agricultural land use decreased between 2007 and 2008 in a manner similar to that observed on the natural levee. For example, the area of single cropping was reduced in 2008 compared to 2007, while the area of multiple cropping increased.

Sediment deposition in the back swamp areas was recorded as 4mm and 19mm, with median grain sizes of 31μm and 105μm (textural class coarse silt and very fine sand) in 2007 and 2008, respectively. These sediment characteristics meant that the land was suitable only for mixed paddy, cromprising *aus*, shallow water *aman* (*Dhigha aman*) and deep water *aman* (*Vasha aman*).

Table6.7 and figure 6.10 show the spatial distribution of agricultural land use dynamics during the pre-monsoon seasons in 2007 and 2008. Only 17 ha were under a single crop in 2007, but this rises to 52 ha in 2008 – an increase of 206%. Conversely, the 186 ha of land featuring multiple cropping in 2007 is reduced by 19% to just 151 ha in 2008. In term of land holdings, 309 plots changed from multiple to single cropping during the pre-monsoon season between 2007 and 2008.

These records illustrate the sensitivity and responsiveness of decision making concerning agricultural land use to annual sedimentation thicknesses and grain size characteristics and, hence, variability in the magnitude and duration of each monsoon flood event.

6.3.1.3 Agricultural land use dynamics during the monsoon seasons of 2007 and 2008

All the agricultural land in the field study area was inundated by river floodwater during the monsoon season 2007 due to the catastrophic nature of the flood (*Bonna*). Shallow water paddy (*T.aman/dhigha aman*), deep-water paddy (*vasha aman*), jute and sugarcane were the main crops.

The extent of flooding was lower during the monsoon in 2008 because this was a normal flood event (*Barsha*). Table 6.8 lists the land use and sediment characteristics of the study area in relation to the landform units and Table 6.9 lists summary statistics for paddy and cash crops observed during the monsoon seasons of 2007 and 2008.

On the natural levee, 16 hectares lands were under single crop, T. *Aman* paddy in 2007 but this fell to just 8 hectares in 2008. No cash crops were cultivated in 2007, but 11 ha of jute and 5 ha of *sesbania (danchaya)* were grown in 2008. 18 hectares of land that was fallow in 2007 came into production in 2008. On the back slope, the area devoted to paddy decreased markedly between 2007 and 2008 monsoon seasons. For example, 46 and 14 ha of transplanted *aman* paddy were planted in 2007 and 2008, respectively.

The corresponding figures for deep-water (*vasha aman)* paddy were 94 and 62 ha. Cash crop cultivation also suffered in the catastrophic flood of 2007, being reduced from 14 ha of jute and 10 ha of sugarcane 2008 to zero. Altogether, 88 ha of croplands were lost to production in 2008, of which 40 ha were fallow due to sand deposition. This demonstrates that farmers on the back slope were unable to grow crops on a relatively large area of the back slope during the 2008 monsoon season in response to severe flooding and sand deposition.

Farmers in the low-lying, frequently flooded back swamp land unit are well accustomed to selecting crops that are appropriate to the expected depth of floodwater. In 2007, there were 8 ha of deep-water paddy (*vasha aman),* but this increased to 13 ha in 2008. This suggests that farmers decided, based on the 2007 flood experience, to plant more deep-water paddy in this low lying area because this is best able to cope with intensive flooding. In fact, 3 ha of land that was fallow in 2007 were brought into production during the monsoon season in 2008.

Average sediment characteristics in each landform unit are also listed in Table 6.8. These are based on the suspended sediments sampled during flood seasons. The results reveal that suspended sediment concentrations were highest on the natural levee (2.63g/l and 2.10g/l in 2007 and 2008, respectively),

Table 6.5 Land use dynamics in different landform units and sediment types during the pre-monsoon seasons in 2007 and 2008

Land use types and Sediment characteristics			Landform Unit								
			Natural levee			Back slope			Back swamp		
			2007	2008	Variation	2007	2008	Variation	2007	2008	Variation
Land use types	Food crops: Paddy (ha)	*Aus*	10	2	-8	16	0	-16	0	0	0
		Single (Shallow, *aman-dhigha*)	9	0	-9	27	0	-27	0	0	0
		Single (Deep, *aman* (*Vasha*))	9	0	-9	23	0	-23	6	7	+1
		Mixed (*Aus & Dhigha*)	7	6	-1	11	64	+53	0	0	0
		Mixed (*Aus & Vasha*)	0	0	0	39	61	+22	10	6	-4
	Cash crops (ha)	Jute	0	7	+7	14	15	+1	0	0	0
		Sugarcane	3	0	-3	10	0	-10	0	0	0
		Sesame	6	13	+7	0	0	0	0	0	0
		Dhanchya (Sesbania)	0	5	+5	0	0	0	0	0	0
	Current fallow land (ha)	Due to sand deposition	0	11	+11	0	0	0	0	0	0
	Non-agricultural use (ha)	Road	3	3	0	3	3	0	0	0	0
		Settlement	13	13	0	28	28	0	0	0	0
	Water bodies (ha)	Distributary of Jamuna River	9	9	0	0	0	0	0	0	0
		Khal (Temporary water flow)	0	0	0	7	7	0	0	0	0
		Rain-fed water logging	0	0	0	0	0	0	0	3	+3
		Perennial water logging	0	0	0	0	0	0	2	2	0
Average Sediment Characteristics		Sediment deposition (cm)	2	5	3	1.5	3	1.5	0.4	2	1.6
		Grain size (µm)	210	260	50	29	57	28	7	14	7
		Textural class	FS	MS	CSI	MSI	CSI	MSI	VFSI	FSI	VFSI

[FS = Fine Sand; MS = Medium Sand; CSI = Coarse Silt; MSI = Medium Silt; FSI = Fine Silt; VFSI = Very Fine Silt]

Table 6.6 Land use change of agricultural crops during the pre-monsoon seasons of 2007 and 2008.

Land use types		**Landforms**								
		Natural levee			**Back slope**			**Back swamp**		
		2007	**2008**	**Variation**	**2007**	**2008**	**Variation**	**2007**	**2008**	**Variation**
Food crops: Paddy (ha)		35	8	-27	116	125	+9	16	13	-3
Cash crops (ha)	Jute	0	7	+7	14	15	+1	0	0	0
	Sugarcane	3	0	-3	10	0	-10	0	0	0
	Sesame	6	13	+7	0	0	0	0	0	0
	Dhanchya (Sesbania)	0	5	+5	0	0	0	0	0	0
Fallow due to sand deposition (ha)		0	11	+11	0	0	0	0	0	0

Table 6.7 Variation of agricultural crops land in terms of plots and total area during the pre-monsoon seasons of 2007 and 2008

Land use types	**Number of plots in use**		**Area (ha)**		**Variation (%)**
	2007	**2008**	**2007**	**2008**	
Single crop	179	488	17	52	206
Multiple crops	1548	1239	186	151	-19

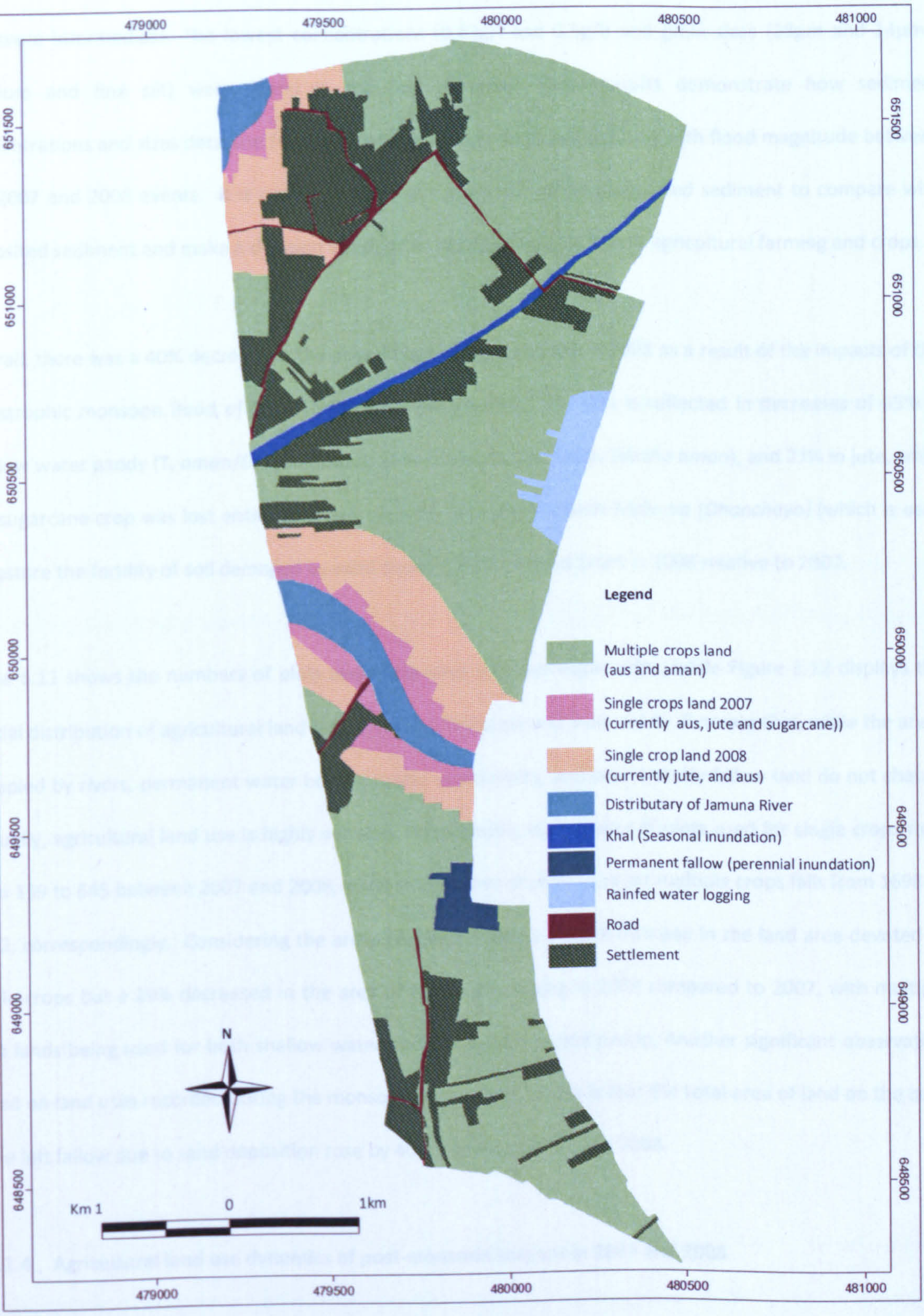


Figure 6.10 Spatial distribution of agricultural land use dynamics during the pre-monsoon seasons of 2007 and 2008

with grain sizes in fine sand and very fine sand categories (128 and 90μm, in 2007 and 2008, respectively). On the back slope, concentrations (1.27g/l and 1.20 g/l) and grain sizes (95 and 58μm - very fine sand and coarse silt) were intermediate. The lowest concentrations (0.83g/l and 0.5g/l) and grain sizes (28μm and 14μm - medium and fine silt) were found in the back swamps. These results demonstrate how sediment concentrations and sizes decrease from the natural levee to back swamps and with flood magnitude between the 2007 and 2008 events. It is crucial to know the grain size of the suspended sediment to compare with deposited sediment and make a decision which grain needs to trap for better agricultural farming and crops.

Overall, there was a 40% decrease in the area of agricultural land use in 2008 as a result of the impacts of the catastrophic monsoon flood of 2007 (Table 6.10 and Figure 6.11). This is reflected in decreases of 65% in shallow water paddy (T. *aman/Dhigha aman*), 26% in deep-water paddy (*Vasha aman*), and 21% in jute, while the sugarcane crop was lost entirely. Conversely, the area planted with *Sesbania* (*Dhanchaya)* (which is used to restore the fertility of soil damaged by sand deposition) increased 100% in 2008 relative to 2007.

Table 6.11 shows the numbers of plots and areas used to grow single crops, while Figure 6.12 displays the spatial distribution of agricultural land use dynamics. The table and map clearly illustrate that, while the areas occupied by rivers, permanent water bodies, roads, settlements, and permanently fallow land do not change annually, agricultural land use is highly variable. For example, the number of plots used for single crops rises from 139 to 645 between 2007 and 2008, while the number of plots used for multiple crops falls from 1698 to 1192, correspondingly. Considering the areas involved, there is a 446% increase in the land area devoted to single crops but a 29% decreased in the area of multiple cropping in 2008 compared to 2007, with multiple crop lands being used for both shallow water and deep water *aman* paddy. Another significant observation based on land uses recorded during the monsoon season field survey is that the total area of land on the back slope left fallow due to sand deposition rose by 40 ha between 2007 and 2008.

6.3.1.4 Agricultural land use dynamics of post-monsoon seasons in 2007 and 2008

The post-monsoon season starts with the floodwater recession in the autumn and continues until March the following year. This period, which produces crops associated with the cool, dry winter, is known as the *rabi* crop season. This section reports on agricultural land use dynamics during the post-monsoon seasons of 2007 and 2008. These reflect the differing magnitudes of the flood events. However, it is important to note that there was no variation in the non-agricultural land uses, including roads, settlements, and permanent water bodies.

The *rabi* crops are divided into two groups: food crops (wheat, pulses and *boro* paddy) and cash crops (oilseeds and nuts). Spatial and temporal variations in post-monsoon agricultural land use are listed in Table 6.12, together with average sediment characteristics.

On the natural levee, 8 ha of land were used for wheat cultivation in 2007, rising to 14 ha in 2008. The equivalent figures for the back slope were 22 and 34 ha. No wheat was grown in the back swamps. Overall, there was an increase of 60% land in wheat cultivation in 2008 (Table 6.13).

In case of pulses, 12, 21 and 7 ha were cultivated in 2007 on the natural levee, back slope and back swamps, respectively. These areas increased to 18, 40 and 8 ha, respectively, in 2008. This represents an overall increase of 65% in pulses in 2008. The only *boro* paddy crop grown in the study area was in the back swamps and this was unchanged at 5 ha in both years.

In 2007, 5, 94 and 4 ha of land were used to grow oil seed on the natural levee, back slope and back swamp, respectively. The equivalent figures for 2008 were 8, 116 and 3ha, representing an overall increase of 23% in oil seed cultivation in 2008.

On the natural levee 10 ha of land were used for nut farming in 2007, rising to 13 ha in 2008. However, on the back slope, the area devoted to nuts decreased from 10 ha in 2007 to only 3 ha in 2008. No nuts were farmed in the back swamps.

Overall, 198 ha of land were used for *rabi* crops in the post-monsoon season of 2007 and this figure rose to 260 ha in 2008; 31% increase. The greatest increase occurred in pulses (65%), there was no change in *boro* paddy and a substantial decrease (-30%) in nut farming (Table 6.13 and Figure 6.13).

The agricultural land was further classified into one of two categories; single crop or multiple crop land, based on number of crops usually produce on a piece of land for the entire the year. The results showed that 320 plots (33 ha) supported a single crop in 2007, while 1518 plots (182 ha) supported multiple crops that year. The equivalent figures for 2008 were 122 plots (12 ha) and 1716 plots (203 ha). This indicates a decrease of 64% in the land area used for a single crop and a 12% increase the area land supporting multiple crops (Table 6.14 and Figure 6.14). Field observations reveal that about 15 ha of land were classed as currently fallow due to sand deposition of 2007, but only 6 ha were same classed in 2008 because sand deposition was less extensive under the *barsha* flood conditions.

The average sediment characteristics observed during the two post-monsoon seasons are also listed in Table 6.12. The sediment characteristics used to describe post-monsoon conditions in 2007 are actually derived from the survey of freshly deposited sediments conducted during the pre-monsoon period in 2008, the reasonable assumption being that no sediment was added or removed during the dry, winter season. For 2008, a sediment survey was performed during the post-monsoon season that year.

On average, d_{90} grain size of 260µm (medium sand) was recorded for the natural levee in post-monsoon season of 2007, while a 180µm (fine sand) was recorded for 2008. The coarser grain size and greater thickness of fresh sediment found following the 2007 flood partially explains why less of the natural levee was used for *rabi* crops in that season, compared to 2008. As it measures 90% of the particles grain size distributions, therefore the values differ with the median (d_{50}) grain presented in chapter 4.

On the back slope, the average thickness of sediment deposited in 2007 was 30mm (57µm - coarse silt) whilst, in 2008 the equivalent figures were 20mm and 28µm (medium silt). Similarly, land use dynamics reflect these changes in the thickness and size of deposited sediments because wheat, pulses and oil seeds are better suited to silt, while nuts can be grown on fine to medium sand.

In the back swamps, the average sediment accumulation was 20mm (median grain size 14µm - fine silt) in 2007, falling to 7mm (median grain size 6µm - very fine silt) in 2008. However, the prominence of *boro* paddy in the back swamps means that there was no significant impact on agricultural land use between the two years.

Table 6.8 Land use dynamics in different landform units and sediment types during monsoon seasons in 2007 and 2008

Land use types and Sediment characteristics			Landform Unit								
			Natural levee			Back slope			Back swamp		
			2007	2008	Variation	2007	2008	Variation	2007	2008	Variation
Land use types	Food crops: Paddy (ha)	*Aus*	0	0	0	0	0	0	0	0	0
		Shallow water (T.*aman-dhigha*)	16	8	-8	46	14	-32	0	0	0
		Deep water *aman* (*Vasha*)	0	0	0	94	62	-32	8	13	5
		Mixed (*Aus & Dhigha*)	0	0	0	0	0	0	0	0	0
		Mixed (*Aus & Vasha*)	0	0	0	0	0	0	0	0	0
	Cash crops (ha)	Jute	0	11	11	14	0	-14	0	0	0
		Sugarcane	0	0	0	10	0	-10	0	0	0
		Dhanchya (Sesbania)	0	5	5	0	0	0	0	0	0
	Current fallow land (ha)		38	20	-18	0	40	40	8	5	-3
	Non-agricultural use (ha)	Road	3	3	0	3	3	0	0	0	0
		Settlement	13	13	0	28	28	0	0	0	0
	Water bodies (ha)	Distributary of Jamuna River	9	9	0	0	0	0	0	0	0
		Khal (Temporary water flow)	0	0	0	7	7	0	0	0	0
		Rain-fed water logging	0	0	0	0	0	0	0	3	+3
		Perennial water logging	0	0	0	0	0	0	2	2	0
Average Sediment Characteristics		Suspended sediment (gm/l)	2.63	2.10	-0.53	1.27	1.20	-0.07	0.83	0.50	-0.33
		Grain size (μm)	128	90	(-)38	95	58	(-)37	28	14	(-)14
		Textural class	FS	VFS	CSI	VFS	CSI	CSI	MSI	FSI	FSI

[FS= Fine sand, VFS= Very Fine Sand, CSI= Coarse Silt, MSI= Medium Silt, FSI= Fine Silt]

Table 6.9 Land use change of agricultural crops during the monsoon seasons of 2007 and 2008.

Land use types		Landform Unit								
		Natural levee			Back slope			Back swamp		
		2007	2008	Variation	2007	2008	Variation	2007	2008	Variation
Paddy (ha)		16	8	-8	140	76	-64	8	13	+5
Cash crops (ha)	Jute	0	11	+11	14	0	-14	0	0	0
	Sugarcane	0	0	0	10	0	-10	0	0	0
	Dhanchya (Sesbania)	0	5	+5	0	0	0	0	0	0
Current fallow land (ha)		38	20	-18	0	40	+40	8	5	-3

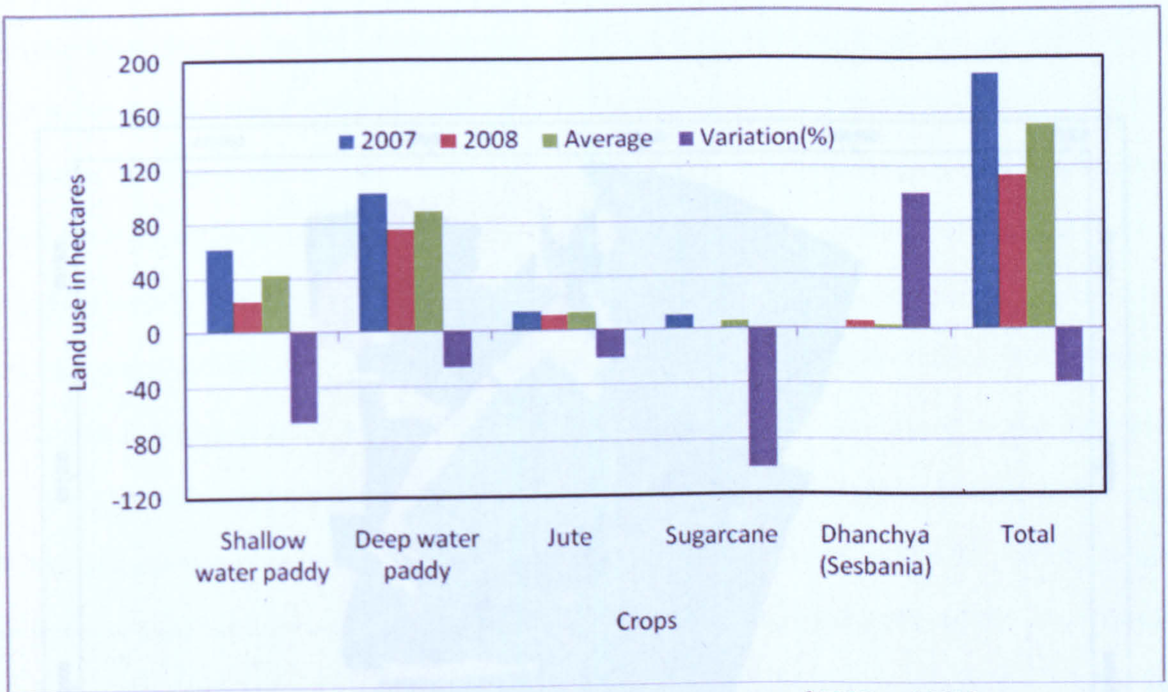


Figure 6.11 Agricultural land use dynamics during the monsoon seasons of 2007 and 2008

Table 6.10 Comparison of agricultural principle cropping land use dynamics during the monsoon seasons of 2007 and 2008

Crops (ha)	2007	2008	Average	Variation (%)
Shallow water paddy (*T.Aman/Dhigha aman*)	62	22	42	-65
Deep water paddy(*Vasha aman*)	102	75	88.5	-26
Jute	14	11	12.5	-21
Sugarcane	10	0	5	-100
Dhanchya (Sesbania)	0	5	2.5	100
Total	188	113	150.5	-40

Table 6.11 Variation of agricultural crops land in terms of plots number and total area of during the monsoon seasons of 2007 and 2008

Land use types	Number of plots in use		Area (ha)		Variation (%)
	2007	2008	2007	2008	
Single crop	139	645	13	71	446
Multiple crops	1698	1192	202	143	-29

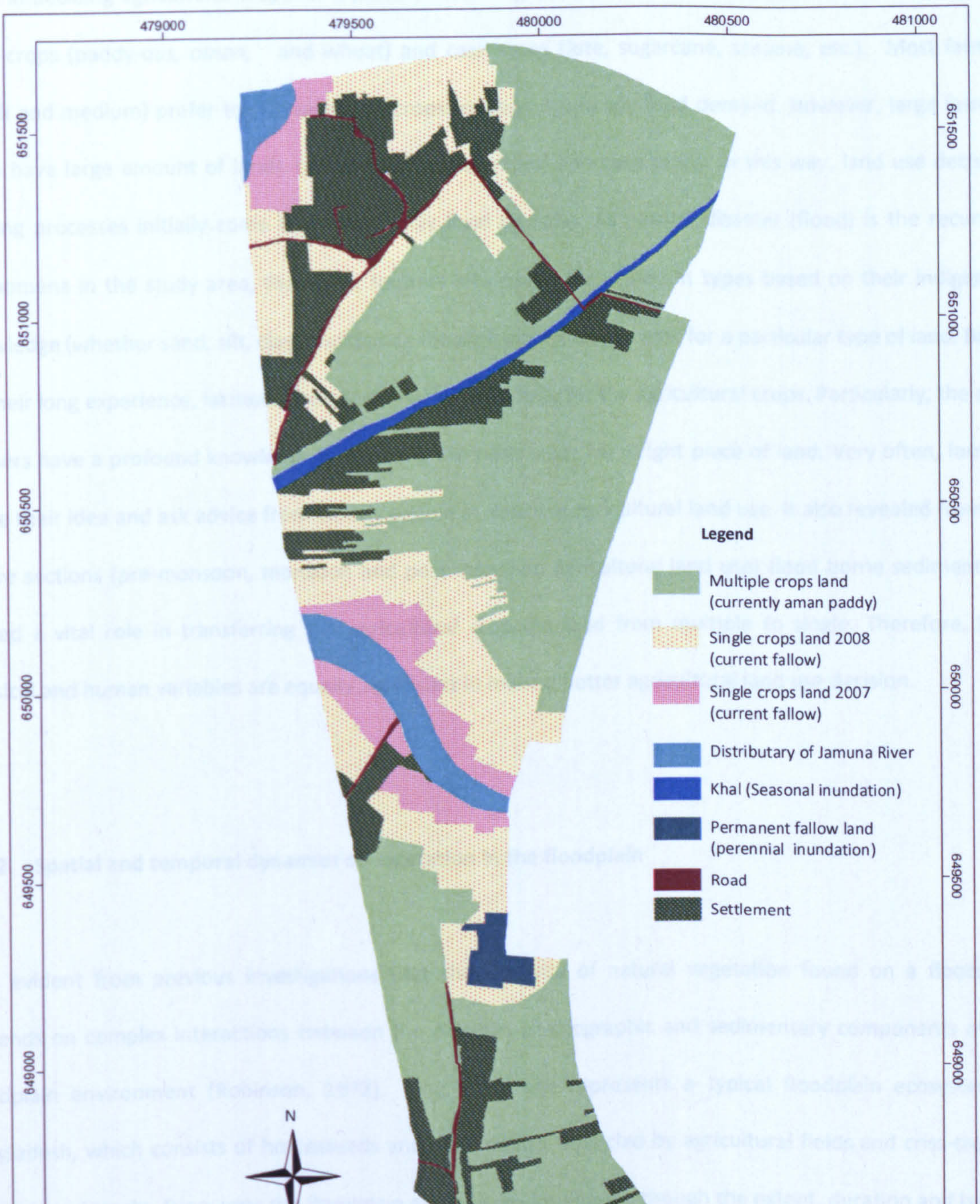


Figure 6.12 Spatial distribution of agricultural land use dynamics during the monsoon seasons of 2007 and 2008.

Land use decision making process

Amongst other variables, farmers mostly consider sediment types, farm size, family size and crop's market price in deciding agricultural crops for a piece of land. Agricultural crops are divided mainly two categories; food crops (paddy-*aus, aman,* and wheat) and cash crops (jute, sugarcane, sesame, etc.). Most farmers (small and medium) prefer to cultivate food crops to meet the family food demand. However, large farmers (who have large amount of land), prefer to grow both food and cash crops. In this way, land use decision-making processes initially come from the family food demand. As natural disaster (flood) is the recurrent phenomena in the study area, therefore, farmers also count the sediment types based on their indigenous knowledge (whether sand, silt, clay) and decide the agricultural crops types for a particular type of land. Based on their long experience, farmers also count the soil suitability for the agricultural crops. Particularly, the aged farmers have a profound knowledge in selecting the right crops for a right piece of land. Very often, farmers share their idea and ask advice from elderly people in deciding agricultural land use. It also revealed from the above sections (pre-monsoon, monsoon and post-monsoon agricultural land use) flood borne sediment has played a vital role in transferring the agricultural cropping land from multiple to single. Therefore, both physical and human variables are equally significant in making better agricultural land use decision.

6.3.2 Spatial and temporal dynamics of vegetation in the floodplain

It is evident from previous investigations that the diversity of natural vegetation found on a floodplain depends on complex interactions between the climatic, physiographic and sedimentary components of the floodplain environment (Robinson, 1972). The study site represents a typical floodplain ecosystem in Bangladesh, which consists of homesteads and settlements, encircled by agricultural fields and criss-crossed by roads and tracks. Every year the floodplain experiences inundation though the extent, duration and type of flooding (river or rain-fed) vary. Floods, and the nutrients and alluvium they carry, generate a habitat capable of supporting rich biodiversity. This is the case due to variability in the floodplain environment associated with topography, hydrology and sedimentology. For example, natural levees and ridges experience relatively shallow inundation due to their higher elevation, while their significant slopes induce considerable flow velocities that deposit relatively coarse sediments. Conversely, back swamps feature semi-permanent,

Table 6.12 Land use dynamics in different landform units and sediment types during post-monsoon seasons in 2007 and 2008

Land use and Sediment characteristics			Landform Units								
			Natural levee			Back slope			Back swamp		
			2007	2008	Variation	2007	2008	Variation	2007	2008	Variation
Land use types	*Rabi* food crops (ha)	Wheat	8	14	6	22	34	14	0	0	0
		Pulses	12	18	-6	21	40	19	7	8	1
		Boro paddy	0	0	0	0	0	0	5	5	0
	Rabi cash crops (ha)	Oil seeds	5	8	3	94	116	22	4	3	-1
		Nut	10	13	3	10	3	-7	0	0	0
	Current fallow land (ha)		15	6	-9	0	0	0	0	0	0
	Non-agricultural use (ha)	Road	3	3	0	3	3	0	0	0	0
		Settlement	13	13	0	28	28	0	0	0	0
	Water bodies (ha)	Distributary River of Jamuna	9	9	0	0	0	0	0	0	0
		Khal (Seed bed for paddy)	0	0	0	7	5	-2	0	0	0
		Perennial water logging	0	0	0	0	0	0	2	2	0
Sediment Characteristic		Sediment deposition(cm)	5	3	-2	3	2	-1	2	0.7	-1.3
		Grain size (µm)	260	180	(-) 80	57	28	(-)29	14	6	(-) 8
		Textural class	MS	FS	VFS	CSI	MSI	MSI	FSI	VFSI	FSI

[MS = Medium Sand; FS = Fine Sand; VFS= Very Fine Sand; CSI = Coarse Silt; MSI = Medium Silt; FSI = Fine Silt; VFSI = Very Fine Silt]

Table 6.13 Variation of Agricultural crops land use frequency of post monsoon season in 2007 and 2008 (in hectares)

Crops	2007	2008	Average	Variation (%)
Wheat	30	48	39	60
Pulses	40	66	53	65
Oil seeds	103	127	115	23
Nuts	20	14	17	-30
Boro paddy	5	5	5	0
Total	198	260	229	31

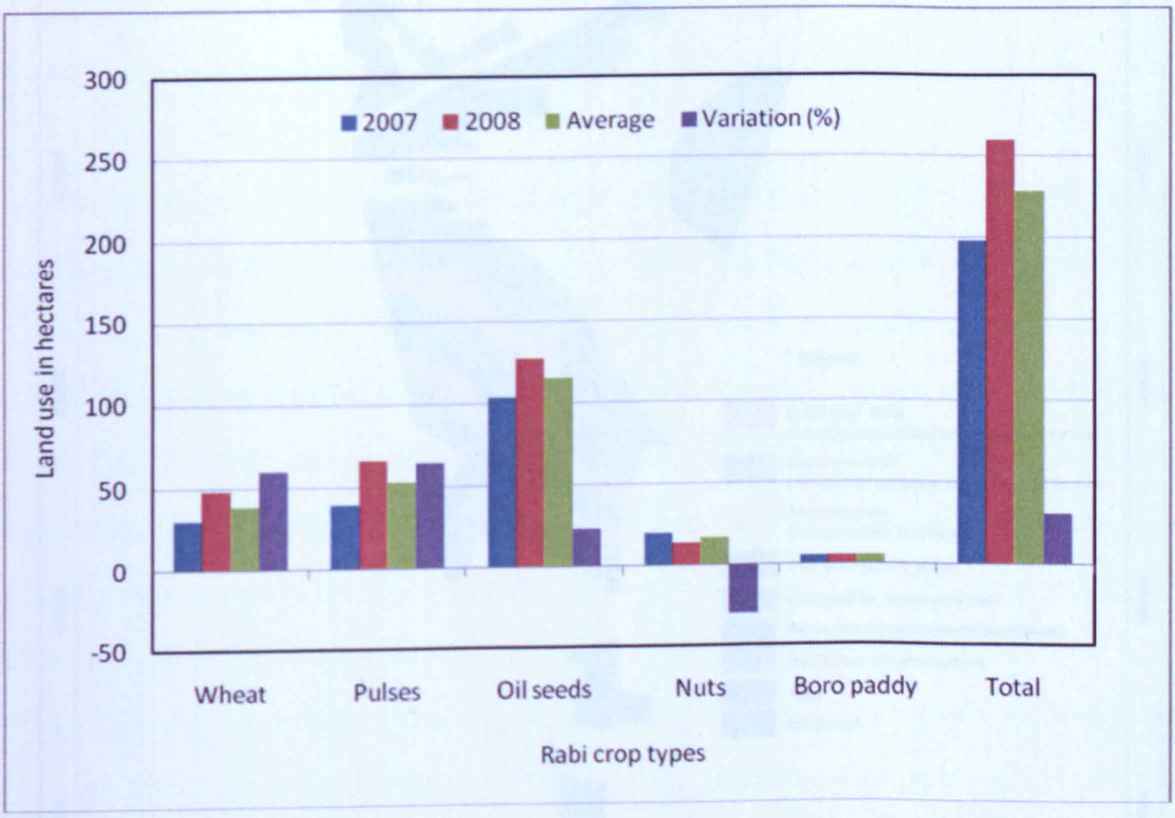


Figure 6.13 Variation of agricultural land use in post-monsoon seasons of 2007 and 2008

Table 6.14 Variation of agricultural crops land in terms of plots number and total area of post-monsoon seasons in 2007 and 2008

Land use types	**Number of plots in use**		**Area (hectares)**		**Variation (%)**
	2007	**2008**	**2007**	**2008**	
Single crop land	320	122	33	12	-64
Multiple crops land	1518	1716	182	203	12

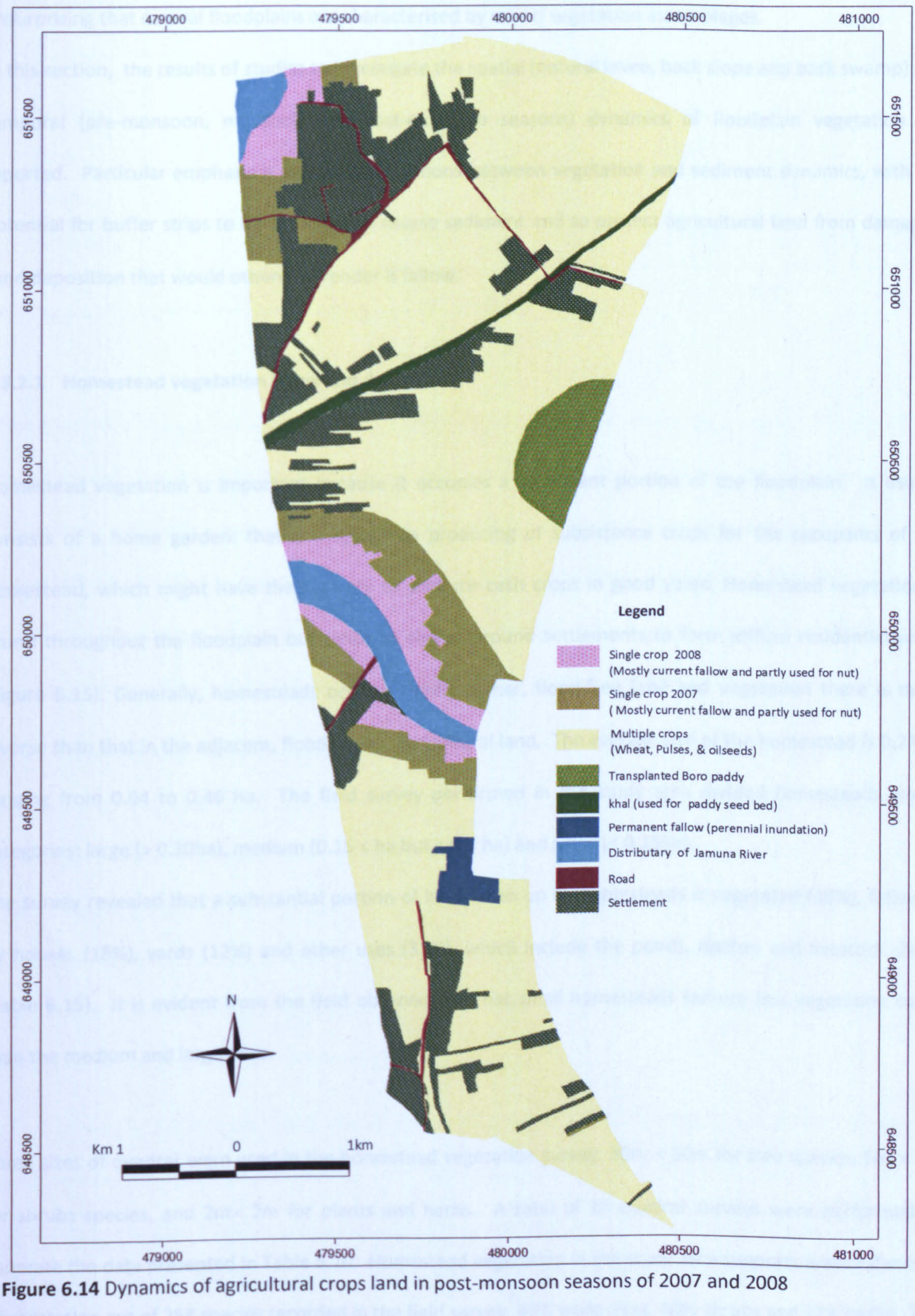


Figure 6.14 Dynamics of agricultural crops land in post-monsoon seasons of 2007 and 2008

stagnant water bodies (*beels*) underlain by fine silts. Given the high degree of habitat diversity, it is unsurprising that natural floodplains are characterised by mixed vegetation assemblages.

In this section, the results of studies to investigate the spatial (natural levee, back slope and back swamp) and temporal (pre-monsoon, monsoon and post-monsoon seasons) dynamics of floodplain vegetation are reported. Particular emphasis is given to interactions between vegetation and sediment dynamics, with the potential for buffer strips to be used to trap coarse sediment and so protect agricultural land from damaging sand deposition that would otherwise render it fallow.

6.3.2.1 Homestead vegetation types and dynamics

Homestead vegetation is important because it occupies a significant portion of the floodplain. It usually consists of a home garden: that is a system in producing of subsistence crops for the occupants of the homestead, which might have the capacity to produce cash crops in good years. Homestead vegetation is found throughout the floodplain but tends to cluster around settlements to form diffuse residential areas (Figure 6.15). Generally, homesteads occupy slightly higher, flood-free land and vegetation there is more diverse than that in the adjacent, flood-prone, agricultural land. The average size of the homestead is 0.24ha, ranging from 0.04 to 0.46 ha. The field survey performed in the study area divided homesteads into 3 categories: large (> 0.30ha), medium (0.15 < ha but < 0.3 ha) and small (< 0.15ha).

The survey revealed that a substantial portion of land taken up by homesteads is vegetated (38%), followed by houses (18%), yards (12%) and other uses (32%), which include the ponds, ditches and livestock sheds (Table 6.15). It is evident from the field observations that small homesteads feature less vegetation cover than the medium and large ones.

Three sizes of quadrat were used in the homestead vegetation survey: 30m × 30m for tree species, 5m × 5m for shrubs species, and 2m× 2m for plants and herbs. A total of 10 quadrat surveys were performed to generate the data presented in Table 6.16. Homestead vegetation in the study area supports a wide diversity of vegetation out of 268 species recorded in the field survey, 48% were trees, 40% shrubs and 12% herbs. The diversity of tree species was greatest with 129 types in 18 family groups, with 27 species. However, diversity was also high in shrubs (108 types in 12 family groups with 13 species) and herbs (31 types in 5 family groups with 5 species).

Table 6.15 Homestead land uses by area

Homestead category	Area of homestead under different uses (ha)				
	House	Vegetation	Yard	Other	Total
Small	0.014	0.017	0.007	0.002	0.04
Medium	0.035	0.061	0.021	0.093	0.21
Large	0.080	0.190	0.060	0.130	0.46
Total	0.13	0.27	0.09	0.23	0.71
Average	0.04 (18) *	0.09 (38)	0.03 (12)	0.08(32)	0.24 (100)

* figures in parentheses indicate the average percentage of utilization

Among the tress the palmae species (coconut, date palm, betel nut, Palmyra etc.) account for 14% of the population, followed by leguminosae (tamarind, white *sirish* and *jhunghuna koroi*, etc.) and Anacardiaceae (mango and wild mango) each of which make up 11% of the population. The remainder of the population includes 15 different family groups none of which makes up more than 4% of the tree population (accacia, blackberry, elephant apple, drumstick, elephant apple, fruit, *higal*, jackfruit, *jiga*, jujube fruit, *kadamba*, litchi, mahogany, *neem*, olive plant, red silk cotton tree, river ebony, tropical almond).

Within the shrubs, myrtaceae (20%); Guava (*Psidium guajava Linn.*) and gramine (15%); Bamboo (*Bambusa Balcooa Roxb.*) musaceae (10%); banana (*Musa sapientum Linn.*), were the dominant species. Almost 60% of homesteads cultivate plants and herbs, with vegetables and cooking herbs dominating. Umbelliferae were the most abundant species (32%), including mainly coriander species (*Coriandrum sativum Linn*), follwed by basellaceae (26%); and Indian Spinach (*Basella alba Linn.*). Cucurbitaceae species were also widely grown herbs, including wax gourd (*Benincasa hispida T.*), rubiaceae mainly paderia (*Paederia foetida Linn.*), and apiaceae consisting of *gotu kola*(*Centella asiatica* Linn).

Table 6.17 and figure 6.16 detail the results of quantitative analysis of homestead vegetation and give an overall impression of its ecological importance. The maximum densities recorded for tree, shrub and herbs plant species were 13, 11 and 3 per quadrat. Five frequency classes are commonly used in botanical sciences to define the frequency range of species in a particular habit. Class A ranges from 1 to 20%, class B - 21% to 40%, class C -41% to 60%, class D - 61%to 80% and class E - 81% to 100% (Raunkiaer, 1934). By this classification, tree species fall into class C, while shrubs and plant/herbs both fall into class B. With respect to vegetation abundance, an index is used. A plant is classed as rare if the number of individuals ranges from 1

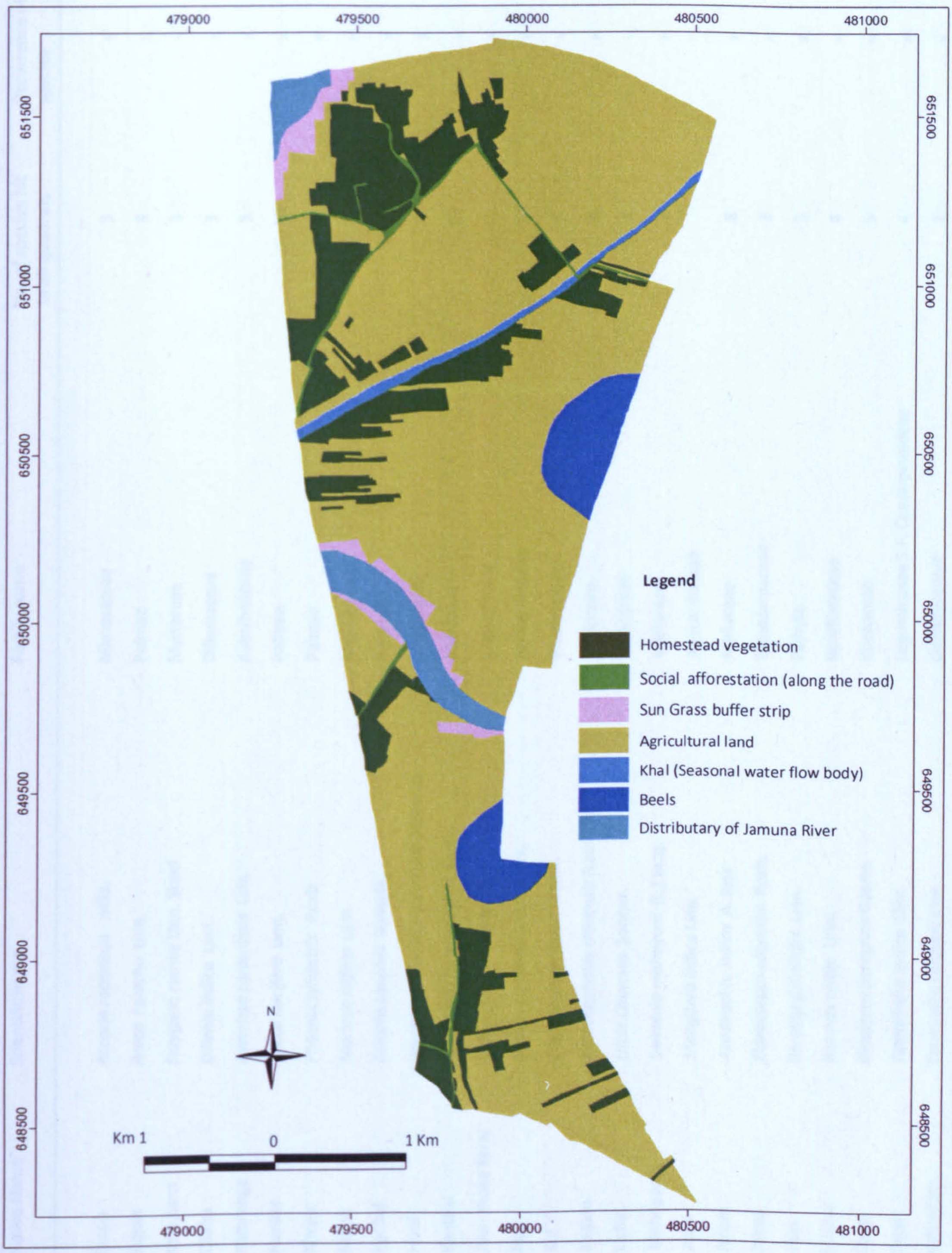


Figure 6.15 Distribution of homestead vegetation in the study area.

Table 6.16 Vegetation diversity in the homestead (continued....)

Plant species	Native Name	Scientific name	Family name	No. of species hit in all quadrats	Occurrence of species
Trees:					
Accacia	Ekasia	*Accacia racemosa* willd.	Mimosaceae	3	×
Betel nut	Supari	*Areca catechu* Linn.	Palmae	9	×
Blackberry	Kalo jaam	*Syzygium cumini* Linn. Skeel	Myrtaceae	3	×
Chalta, Elephant apple	Chalta	*Dillenia indica* Linn.	Dilleniaceae	3	×
Chinese Gooseberry	Kamranga	*Averrhoa carambola* Linn.	Averrhoaceae	5	×
Coconut	Narikel	*Cocos nucifera* Linn.	Palmae	10	×
Date Palm	Khejur	*Phoenix sylvestris* Roxb	Palmae	5	×
Drumstick	Sajina	*Moringa olifera* Lam.	Moringaceae	5	×
Elephant apple, Monkey Fruit	Kadbel	*Feronia Limonia* Swingle.	Rutacea	2	×
Higal	Hizol	*Barringtonia acutangula* (Linn.) Gaertn.	Myrtaceae	3	×
Jackfruit	Kanthal	*Artocarpus heterophyllus* Lamk.	Moraceae	10	×
Jhunghuna Koroi	Jhun Jhona karai	*Dalbergia lanceolaria* Linn.	Leguminosae	2	×
Jiga	Jiga	*Lannea coromandelica* Merr.	Anacardiaceae	10	×
Jujube Fruit	Kul	*Zizyphus mauritiana* Lamk.	Rhamanaceae	4	×
Kadamba	Kadam	*Anthocephalus chinensis* (Lam.) Rich	Rubiaceae	8	×
Litchi	Lichu	*Litchi Chineses* Sonner.	Sapindceae	1	×
Mahogany	Mehogony	*Swetenia mahagoni* (L.) Jacq.	Meliaceae	5	×
Mango	Aam	*Mangifera indica Linn.*	Anacardiaceae		
Neem	Neem	*Azadirachta indica* A. Juss	Meliaceae	8	×
Olive plant	Jalpai	*Elaeocarpus robustus* Roxb.	Elaeocarpaceae	3	×
Palmyra Palm	Taal	*Borasus flabellifer* Linn.	Palmae	5	×
Red Silk cotton Tree	Shimul	*Bombax ceiba* Linn.	Bombacaceae	4	×
River ebony	Gaab	*Diospyros peregrine* Gaertn	Ebenaceae	5	×
Tamarind	Tetul	*Tamarindus indica* Linn.	Leguminosae S.F. Caesalpinoideae	4	×
Tropical Almond	Katbadam	*Terminalia catappa* Linn.	Combretaceae	2	×

Table 6.16 Vegetation diversity in the homestead (end)

Plant species	Native Name	Scientific name	Family name	No. of species hit in all quadrats	Occurrence of species
White Sirish	Shil karai	*Albizia procera* Benth.	Leguminosae S.F. Mimosoideae	2	×
Wild Mango	Amra	*Spondias pinnata Kurz.*	Anacardiaceae	5	×
Wood Apple	Bel	*Aegle marmelos* Linn.	Rutaceae	3	×
Total			**18**	**129**	**27**
Shrubs					
Bamboo	Baas	*Bambusa Balcooa* Roxb.	Gramine	8	×
Banana	Kola	*Musa sapientum* Linn.	Musaceae	3	×
Barbados Nut, poison Nut	Verenda	*Jatropha curcus* Linn.	Euphorbiaceae	4	×
Common Basil	Tulsi	*Ocimum sanctum,* Linn.	Lamiaceae (Labiatae)	4	×
Green chili	Kacha morich	*Capsicum annum* Linn.	Solanaceae	25	×
Guava	Peara	*Psidium guajava* (Linn.) Bat.	Myrtaceae	3	×
Apple guava	Kazi peara	*Psidium guajava* Linn.	Myrtaceae	2	×
Ladies finger	Dheros	*Abelmoschus esculentus* (Linn.) Moen.	Malvaeae	8	×
Lemon	lebu	*Citus spp.*	Rutaceae	6	×
Papaya	Pepe	*Carica papaya* Linn.	Caricacea	20	×
Pomegranate	Dalim	*Punica granatum* Linn.	Punicaceae	4	×
Shaddock, Pummelo	Jambura	*Citrus grandis L.*	Citraceae	6	×
Turmaric	Holud	*Curcuma domestica Vahl.*	Zingiberaceae	15	×
Total			**12**	**108**	**13**
Herbs					
Wax gourd	Chal Kumra	*Benincasa hispida T.*	Cucurbitaceae	5	×
Coriander	Dhania	*Coriandrum sativum Linn*	Umbelliferae	10	×
Paderia	Gandha bhaduli	*Paederia foetida Linn.*	Rubiaceae	2	×
Gotu kola	Thankuni	*Centella asiatica* Linn. Urban.	Apiaceae	6	×
Indian Spinach	Puisaak	*Basella alba* Linn.	Basellaceae	8	×
Total			**5**	**31**	**5**

Table 6.17 Density, frequency and abundance of vegetation at Homestead.

Types	Total no. of species	Density	Relative density(%)	Frequency (%)	Relative Frequency(%)	Abundance
Trees	129	13	48	60	46	47
Shrubs	108	11	40	40	31	39
Herbs	31	3	12	30	23	14

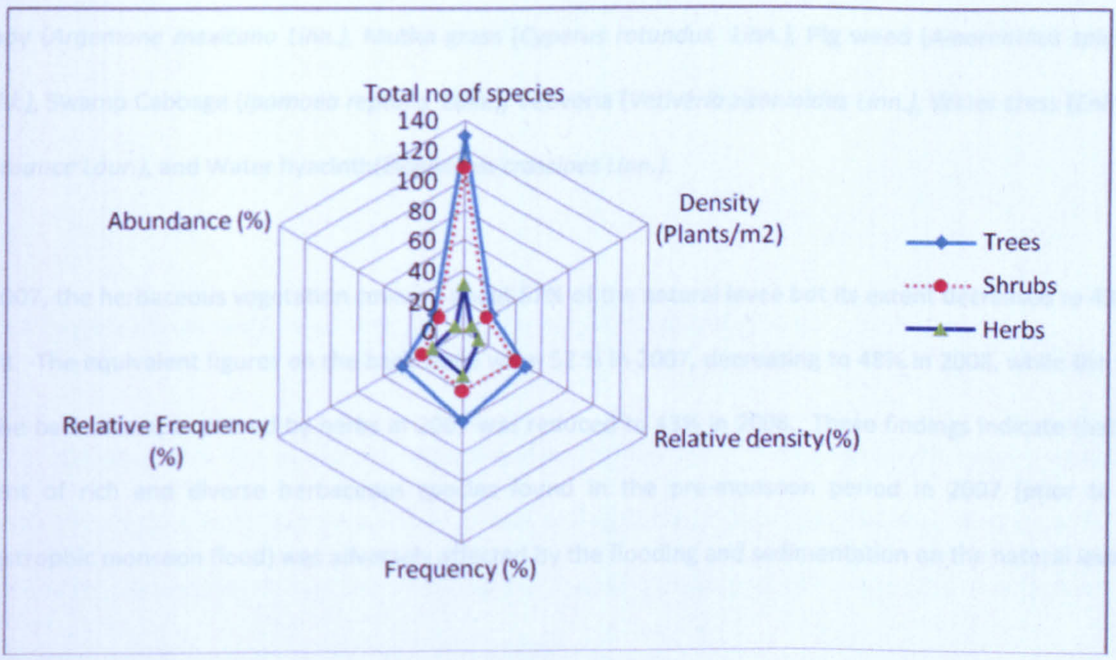


Figure 6.16 Homestead vegetation diversity

to 4 per square metre, occasional (5 to 14), frequent (15 to 29), abundant (30 to 90) and very abundant (>100). On this scale, the trees and shrubs are both abundant, while herbs fall into the occasional class. In summary, the results of the vegetation survey present a picture of the homestead vegetation that is diverse and abundant in both the active and young floodplain portions of the study area.

6.3.2.2 Vegetation diversity in agricultural land during the pre-monsoon season

The environmental attributes of agricultural land in the floodplain are highly dynamic due to annual and inter-annual variability in water levels associated with monsoonal flooding, which drives changes in the characteristics of the surficial sediments that affect soil fertility and the types of crop that are planted. Thus, both edaphic and climatic variables are responsible for vegetation dynamics and diversity.

The vegetation survey showed that agricultural land in the study area supports a diverse population of natural species during the pre-monsoon season, belonging to 26 angiosperm families and rich in shrubs, grasses, herbs and sedges (Table 6.18). 12 different species of herbs and 14 species of shrubs were identified. The main herbs species were Asparagus (*Asparagus racemosus Linn.),* Caugh Grass(*Cynodon dactylon Pers.),* Rice (*Oryza sativa L.inn),* Hydrilla (*Hydrilla verticillata Linn.),* Indian Spinach (*Basella alba Linn.),* Mexican Prickly poppy (*Argemone mexicana Linn.),* Mutha grass (*Cyperus rotundus Linn.),* Pig weed (*Amaranthus spinosus Willd.),* Swamp Cabbage (*Ipomoea reptans Linn.),* Vetiveria (*Vetiveria zizanioides Linn.),* Water cress (*Enhydra fluctuance Lour.),* and Water hyacinth(*Eichhornia crassipes Linn.).*

In 2007, the herbaceous vegetation covered about 57% of the natural levee but its extent decreased to 43% in 2008. The equivalent figures on the back slope were 52 % in 2007, decreasing to 48% in 2008, while the 57% of the back swamps covered by herbs in 2007 was reduced to 43% in 2008. These findings indicate that the extent of rich and diverse herbaceous species found in the pre-monsoon period in 2007 (prior to the catastrophic monsoon flood) was adversely affected by the flooding and sedimentation on the natural levee.

The major shrub species recorded on the natural levee include Arundo (*Arundo donax Linn.),* Colocasia (*Colocasis nymphaefolia Kunt.),* Green chilli (*Capsicum annum Linn.)* Guava (*Psidium guajava Linn.),* Ipomoea (*Ipomoea fistulosa Rob.),* Jute (*Corchorus capsularis Linn.),* Kalilota (*Derris trifoliata Lour.),* Lemon (*Citrus aurantifolia Linn.),* Prickly Amaranth (*Amaranthus spinosus Linn.),* Saccharum (*Saccharam Spontaneum Linn.),* Sesame (*Sesamu indicum Linn.),* Sesbania (*Sesbania bispinosa Swatt.),* Sugercane (*Saccharum officinarum Linn.),* Sungrass (*Imperata arundinaceae Linn.).* The area covered by shrubby vegetation decreased from 56% in 2007, to 44% in 2008. Similar reductions in the extents of shrubby vegetation were observed on the back slope (18%) and the back swamps (50%) between 2007 and 2008.

Table 6.19 lists the density, relative density, frequency, relative frequency and abundance of herb and shrub species in agricultural land during the pre-monsoon seasons of 2007 and 2008. Here frequency presents the percentage of vegetation species in a sample unit. Maximum recorded densities for herbs and shrubs are 50 and 38 individuals per square metre, respectively, in 2007, falling to 42 and 28 in 2008. According to Raunkiaer's (1934) frequency class, herb species fall into class D in 2007 and class C in 2008. Shrubs, fall into class D in both years. In terms of relative frequency, herb species decreased 8% and shrubs 6% between 2007 and 2008. These findings demonstrate the adverse impacts of the 2007 flood. However, shrub abundances are in the abundant class for both years.

The survey results also depict the natural richness of creeper-type plants, of which 18 different species are recorded. The principal species is gramineae (24%), followed by Amaranthaceae (8%), convovulaceae (8%), and other species (Araceae, Basellaceae, Compositae, Cyperaceae, Hydrocharitacea, Leguminosae, Liliaceae, Myrtaceae, Papaveraceae, Papilionaceae, Pedaliaceae, Pontederiaceae, Rutaceae, Solanaceae, Tiliaceae) each of which occupies <4% of the natural levee (Table 6.20).

6.3.2.3 Vegetation diversity in agricultural land during the monsoon season

Most of the study area was inundated during the monsoon season. The field surveys revealed a mixture of natural, aquatic vegetation (including shrub species) and agricultural crops that had been planted during the pre-monsoon season and were yet to be harvested. A total of 9 herbal and 10 shrubby species were identified during the monsoon seasons in 2007 and 2008 (Table 6.21).

Agricultural land on the natural levee comprised 62% herbs and 38% shrubs in 2007, decreasing to 51% and 49% in 2008. Dominant herbaceous species included Cynodon (*Cynodon intermedius Pers.)* Mutha grass (*Cyperus rotundus Linn.*) and Rice (*Oryza sativa Linn.)* while shrubs included Guava *(Psidium guajava Linn.),* Helencha *(Alternanthera philoxeroides Mart.),* Ipomoea *(Ipomoea fistulosa Rob.),* Jute *(Corchorus capsularis Linn.),* Saccharum *(Saccharam Spontaneum Linn.),* Sesbania *(Sesbania bispinosa Swatt.),* Sugercane *(Saccharum officinarum Linn.).* Sungrass *(Imperata arundinaceae)* occurred frequently on the natural levee during the monsoon season.

On the back slope, herbaceous species covered 57% of the area in 2007, falling to 43% in 2008. The main species were alternanthera (*Alternathera sessilis* Linn.), cynodon (*Cynodon intermedius Pers.)* mutha grass (*Cyperus rotundus* Linn.), rice (*Oryza sativa L.),* swamp Cabbage (*Ipomoea reptans* Linn.), vetiveria (*Vetiveria zizanioides Linn.)* and water cress (*Enhydra fluctuance* Lour.). Shrub vegetation covered 56% of the back slope

Table 6.18 Vegetation diversity in the area of agricultural land during the pre-monsoon season (continued.....)

Plant species				No. of plants encountered in all quadrats					
Herbs:				Natural levee		Back slope		Back swamp	
English name	**Native name**	**Scientific name**	**Family name**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Asparagus	Satomul	*Asparagus racemosus Linn.*	Liliaceae	4	6	8	3	-	-
Caugh Grass	Durba ghas	*Cynodon dactylon Pers.*	Gramineae	45	30	50	65	-	-
Rice	Dhan	*Oryza sativa L.inn*	Gramineae	40	25	108	90	85	60
Hydrilla	Dal	*Hydrilla verticillata Linn.*	Hydrocharitacea	-	-	-	-	20	16
Indian Spinach	Puisaak	*Basella alba Linn.*	Basellaceae	4	2	6	4	-	-
Mexican Prickly poppy	Shial kata	*Argemone mexicana Linn.*	papaveraceae	3	6	5	10	-	-
Mutha grass	Mothoghas	*Cyperus rotundus Linn.*	Cyperaceae	2	6	1	0	-	-
Pig weed	Notae	*Amaranthus spinosus Willd.*	Amaranthaceae	-	-	14	6	-	-
Swamp Cabbage	Kolmi Saak	*Ipomoea reptans Linn.*	Convolvulaceae	-	-	12	7	3	2
Vetiveria	Binna	*Vetiveria zizanioides Linn.*	Gramineae	10	6	20	25	-	-
Water cress	Hinche saak	*Enhydra fluctuance Lour.*	Compositae	-	-	15	10	25	20
Water hyacinth	Kochuri pana	*Eichhornia crassipes Linn.*	Pontederiaceae	-	-	-	-	16	16
Total				**108**	**81**	**239**	**220**	**149**	**114**
%				**57**	**43**	**52**	**48**	**57**	**43**

Table 6.18 Vegetation diversity in the area of agricultural land during the pre-monsoon season (end)

Plant species				No. of plants encountered in all quadrats					
Shrubs:				Natural levee		Back slope		Back swamp	
English name	**Native name**	**Scientific name**	**Family name**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Arundo	Noal	*Arundo donax Linn.*	Graminae	-	-	7	5	-	-
Colocasia	Jangle Kochu	*Colocasis nymphaefolia Kunt.*	Araceae	-	-	6	8	-	-
Green chili	Kacha morich	*Capsicum annum Linn.*	Solanaceae	30	20	40	25	-	-
Guava	Peara	*Psidium guajava Linn.*	Myrtaceae	2	-	8	4	-	-
Ipomoea	Dhol kolmi	*Ipomoea fistulosa Rob.*	Convolvulaceae	-	-	10	5	6	2
Jute	Paat	*Corchorus capsularis Linn.*	Tiliaceae	40	20	50	40	-	-
Kalilota	Kalilota	*Derris trifoliata Lour.*	Papilionaceae	-	-	4	2	-	-
Lemon	Lebu	*Citrus aurantifolia Linn.*	Rutaceae	4	-	-	-	-	-
Prickly Amaranth	Katanote	*Amaranthus spinosus Linn.*	Amaranthaceae	-	-	10	7	-	-
Saccharum	Kash	*Saccharam Spontaneum Linn.*	Gramineae	30	40		-	-	-
Sesamum	Til	*Sesamu indicum Linn.*	Pedaliaceae	40	20	50	30	-	-
Sesbania	Dhanchya	*Sesbania bispinosa Swatt.*	leguminosae	-	20	-	-	-	-
Sugercane	Akh	*Saccharum officinarum Linn.*	Gramineae	20	-	-	-	-	-
Sungrass	Chonghas	*Imperata arundinaceae Linn.*	Graminae	20	28	-	-	-	-
Total				**186**	**148**	**185**	**126**	**6**	**2**
%				**56**	**44**	**59**	**41**	**75**	**25**

Table 6.19 Density, frequency and abundance of vegetation in the area of agricultural land during the pre-monsoon season

Vegetation type	Total Number of species		Density (Plants/m^2)		Relative Density (%)		Frequency (%)		Relative Frequency (%)		Abundance	
	2007	**2008**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Herbs	496	415	50	42	54	46	70	60	54	46	71	47
Shrubs	377	276	38	28	58	42	80	70	53	47	49	46

Table 6.20 Family wise vegetation diversity in agricultural land during the pre-monsoon season

Sl. No.	Family name	Habit	Occurrence (%)	Order
1	Amaranthaceae	Herb	8	2
2	Araceae	Shrub	4	3
3	Basellaceae	Herb	4	3
4	Compositae	Herb	4	3
5	Convolvulaceae	Herb	8	2
6	Cyperaceae	Herb	4	3
7	Graminae	Shrub	24	1
8	Hydrocharitacea	Herb	4	3
9	Leguminosae	Shrub	4	3
10	Liliaceae	Herb	4	3
11	Myrtaceae	Shrub	4	3
12	Papaveraceae	Herb	4	3
13	Papilionaceae	Shrub	4	3
14	Pedaliaceae	Shrub	4	3
15	Pontederiaceae	Herb	4	3
16	Rutaceae	Shrub	4	3
17	Solanaceae	Shrub	4	3
18	Tiliaceae	Shrub	4	3
	Total		≈100	

in 2007, decreasing to 44 % in 2008. The main shrub species were arundo *(Arundo donax Linn.)*, colocasia *(Colocasis nymphaefolia Kunth)*, guava *(Psidium guajava Linn.)*, helencha *(Alternanthera philoxeroides Mart.)*, ipomoea *(Ipomoea fistulosa Rob.)*, and jute *(Corchorus capsularis Linn.)*.

The back swamp is deeply flooded during the monsoon season and it mainly features floating vegetation together with some deep-water varieties of rice. Consequently, herbaceous plants dominate here. The main species recorded were: alternanthera (*Alternathera sessilis* Linn.), cynodon (*Cynodon intermedius Pers.)*, mutha grass (*Cyperus rotundus Linn.*), rice (*Oryza sativa L.)*, swamp Cabbage (*crassipes*), water lily *(Nymphaea Nouchaea Linn.)*. Just two species of shrub consist were recorded; helencha *(Alternanthera philoxeroides Mart.)* and ipomoea *(Ipomoea fistulosa Rob.)*. In 2007, the herbs (*Ipomoea reptans Linn.*), water cress (*Enhydra fluctuance. Linn.*), water hyacinth (*Eichhornia)* made up 59% of the recorded vegetation, but this percentage fell to just 41% in 2008.

Table 6.22 lists the density, relative density, frequency, relative frequency and abundance of natural vegetation (herbaceous and shrubby species together) in the area of the floodplain classed as agricultural land during the monsoon seasons of 2007 and 2008. The highest densities of herbs and shrubs recorded are 36 and 20 per square metre, respectively, in 2007, decreasing to 34 and 28 in 2008. The relative densities of herbaceous and shrubby vegetation were 59% and 53%, respectively, in 2007, falling to 41% and 47% in 2008. These results demonstrate a marked decrease in the extent of natural vegetation during the monsoon season of 2008 compared to 2007.

Within the vegetation community, individuals of different species were not evenly distributed spatially. Some species were widely dispersed while others were found in clumps or mats. These contrasting distribution patterns relate to the reproductive capacities of the plants as well as their ability to adapt to the changing environment. In this context, frequency refers to the degree of dispersion in terms of percentage occurrence. During the monsoon season, the frequencies of herbs and shrubs both fall into class D in 2007, but slip into class C in 2008. Considering relative frequencies for herbs and shrubs both declined by about 15% in 2008. The calculated value of abundance for herbaceous species was 51 in 2007, falling to 29 in 2008, which indicates that species that were classed as abundant in 2007 were only classed as frequent in 2008. The abundance of shrubby species was found to be 36 (abundant) in 2007, falling to 25 (frequent) in 2008.

12 representative families were recorded during the monsoon season, including both herbaceous and shrubby plants. The graminae family (37%) was most widespread with the convovulaceae family ranked second (13%). Amaran, Amaranthaceae, Araceae, Compositae, Cyperaceae, Leguminosae, Myrtaceae, Nimphacea, Pontederiaceae and Tiliaceae were the other major families encountered, each covering about 5% of the surveyed area (Table 6.23).

6.3.2.4 Vegetation diversity in agricultural land during the post-monsoon season

In October, floodwater starts to recede and farmers plant and start to cultivate dry season, *rabi* crops. During this period, natural and cultivated plants are mixed together complicating identification and classification of the vegetation found in agricultural areas. To overcome this problem, field investigation performed during the post monsoon seasons in 2007 and 2008 drew on observations made during the previous seasons when determining natural vegetation diversity.

On the natural levee in 2007, a total of 392 natural plant species, belonging to 13 families, were encountered at 10 sites surveyed using quadrats (Tables 6.24 - 6.26). 14 herbaceous species were identified, of which the dominant species was gramineae, but the most striking finding was the diversity of natural vegetation, which included; Phyla nodiflora (*Phylla nodiflora Linn.*), Polygonum hydropiper (*Ploygonum hydropiper Linn.),* Hydrilla *(Hydrilla verticillata Linn.),* Cyprus (*Cyprus verticillatra Linn.),* Coriander (*Coriandrum sativum Linn.*), Caugh Grass (*Cynodon dactylon Pers.*), Paspalum (*Paspalum conjugatum Linn.),* Kalakasunda (*Cassia sophera Linn.*), Portulaca (*Portulaca pilosa Linn.),* Vigna *(Vigna mungo Linn.*), Bat lily (*Tacca Leavis Roxb.),* Indian Spinach (*Basella alba Linn.),* and Alternanthera *(Alternathera sessilis Linn.*). However, in 2008, this level of diversity had been reduced as the total number of herbaceous species sampled on the natural levee was down to just 223. About 28% of the species had disappeared due to coarse sedimentation during the catastrophic monsoon flood of 2007.

On the back slope, 559 species of vegetation were recorded in 2007, but this total also decreased in 2008. Just 382 species were recorded in 2008, a reduction of about 18%. In the back swamps, relatively a few herbaceous species (92) were encountered in 2007, with the dominant species being: Phyla nodiflora (*Phylla nodiflora Linn.*), Polygonum hydropiper (*Ploygonum hydropiper Linn.),* Hydrilla *(Hydrilla verticillata Linn.),* Cyprus (*Cyprus verticillatra Linn.)* and Kalakasunda (*Cassia sophera Linn.*). This relatively low diversity was further reduced to 59 species in 2008, a decline of almost 22%.

Diversity was generally lower for shrubby species, with just two species (Sungrass (*Imperata arundinaceae Linn.)* and Green chilli (*Capsicum annum Linn.)*) dominating. Inter-annual trends were similar, with declines of 21%, 36% and 21% being observed on the natural levee, back slope and back swamps, respectively.

Table 6.25 presents the results of quantitative analysis of vegetation diversity during the post-monsoon seasons. In 2007, the number herbaceous and shrubby species recorded were 1043 and 115, respectively. The equivalent figures for 2008 fell to 664 and 86.

Table 6.21 Vegetation diversity in agricultural land during the monsoon season (continued.....)

		Plant species		**No. of plants encountered**					
Herbs:				**Natural levee**		**Back slope**		**Back swamp**	
English name	**Native name**	**Scientific name**	**Family name**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Alternanthera	Sachi Saak	*Alternathera sessilis* (Linn.) DC.	Amaranthaceae	-	-	12	6	16	10
Cynodon	Jal Durba	*Cynodon intermedius Pers.*	Gramineae	2	0	10	6	5	3
Mutha grass	Mothoghas	*Cyperus rotundus* Linn.	Cyperaceae	6	4	8	6	5	3
Rice	Dhan	*Oryza sativa L.*	Gramineae	40	25	108	90	85	60
Swamp Cabbage	Kolmi Saak	*Ipomoea reptans* Linn.	Convolvulaceae	-	-	12	7	3	2
Vetiveria	Binna	*Vetiveria zizanioides Linn.*	Gramineae	-	-	4	0	-	-
Water cress	Hinche saak	*Enhydra fluctuance* Lour.	Compositae	-	-	6	4	14	7
Water hyacinth	Kochuri pana	*Eichhornia crassipes*	Pontederiaceae	-	-	-	-	16	16
Water lily	Sapla	*Nymphaea Nouchaea Linn.*	Nimphacea	-	-	-	-	4	2
Total				**48**	**29**	**160**	**119**	**148**	**103**
%				**62**	**38**	**57**	**43**	**59**	**41**

Table 6.21 Vegetation diversity in agricultural land during the monsoon season (end).

Plant species				No. of species hit in all quadrats					
Shrubs:				**Natural levee**		**Back slope**		**Back swamp**	
English name	**Native name**	**Scientific name**	**Family name**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Arundo	Noal	*Arundo donax* Linn.	Graminae	-	-	7	5	-	-
Colocasia	Jangle Kochu	*Colocasis nymphaefolia Kunth*	Araceae	-	-	6	8	-	-
Guava	Peara	*Psidium guajava* (Linn.) Bat.	Myrtaceae	2	0	8	4	-	-
Helencha	Helencha	*Alternanthera philoxeroides Mart.*	Amaran	-	-	-	-	6	4
Ipomoea	Dhol kolmi	*Ipomoea fistulosa Rob.*	Convolvulaceae	-	-	6	3	8	5
Jute	Paat	*Corchorus capsularis* Linn	Tiliaceae	40	20	50	40	-	-
Saccharum	kash	*Saccharam Spontaneum* (Linn.)	Gramineae	30	40	-	-	-	-
Sesbania	Dhanchya	*Sesbania bispinosa* Swatt.	leguminosae	0	20	-	-	-	-
Sugercane	Akh	*Saccharum officinarum* Linn.	Gramineae	20	0	-	-	-	-
Sungrass	Chonghas	*Imperata arundinaceae*	Graminae	20	28	-	-	-	-
Total				**112**	**108**	**77**	**60**	**14**	**9**
%				**51**	**49**	**56**	**44**	**61**	**39**

Table 6.22 Density, frequency and abundance of vegetation in agricultural land during the monsoon season

Vegetation types	Total Number of species		Density (Plant/m^2)		Relative Density (%)		Frequency (%)		Relative Frequency (%)		Abundance	
	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Herbs	356	251	36	25	59	41	80	60	57	43	51	36
Shrubs	203	177	20	18	53	47	70	50	58	42	29	25

Table 6.23 Family wise vegetation diversity in agricultural land during the monsoon season

Sl. No.	Family name	Type	Occurrence (%)	Order
1	Amaran	Shrub	5	3
2	Amaranthaceae	Herb	5	3
3	Araceae	Shrub	5	3
4	Compositae	Herb	5	3
5	Convolvulaceae	Herb	13	2
6	Cyperaceae	Herb	5	3
7	Graminae	Shrub	37	1
8	leguminosae	Shrub	5	3
9	Myrtaceae	Shrub	5	3
10	Nimphacea	Herb	5	3
11	Pontederiaceae	Herb	5	3
12	Tiliaceae	Shrub	5	3
	Total	=	**100**	

The density of herbaceous species was found to be 104 plants/ m^2 in 2007, which is classed as being in the high category. However, in 2008, the density had dropped to 66 plants/m^2. The equivalent figures for shrubby species were 12 plants/m^2 in 2007, and 9 plants/m^2 in 2008. The relative densities of herbaceous and shrubby plants were calculated to be 61% and 57%, respectively, in 2007, but in 2008 these relative densities had fallen to 39% and 43%, respectively.

The frequency distributions of the herbs and shrubs were 90% and 50% in 2007, and 60% and 40% in 2008, respectively. Hence, herbaceous vegetation was in class E in 2007, but it changed to class C in 2008. The frequency distribution of shrubby vegetation also changed between the two years, from class C in 2007 to class B in 2008. According to the *'frequency law'* developed by Raunkiaer (1934), species with lower frequency values are greater in number than species with higher frequencies, in most natural communities. The relative frequencies of herbs and shrubs also declined between 2007 and 2008, by about 20% and 12%, respectively.

The abundance of herbaceous species was 104 in 2007, declining to 83 in 2008, which indicates that species that were very abundant in 2007 were only abundant in 2008. Shrubby vegetation was categorised as being of occasional abundance in both years.

In total, 13 representative families were recorded during the post-monsoon season, with the gramineae family ranking first in relative abundance (28%). The next to 12 families in rank order were; Amaranthaceae, Basellaceae, Cyperaceae, Hydrocharitacea, Lauraceae, Leguminosae, Polygona, Portulacaceae, Solanaceae, Taccaceae, Umbelliferae and Verbenaceae, with which each family making up around 6% of the total (Table 6.26).

6.3.2.5 Overall vegetation diversity in the study area

It is evident from the results presented thus far that gramineae is the dominant species in the study site. According to the survey, a substantial portion of the land was occupied by gramineae and related species in the poaceae family; principally sun grass (*Imperata cylindrica. Linn.)* on the natural levee, gramineae, amaranthaceae, verbenaceae and polygona (commonly mat grass - *Hemarthria altissima*) on the back slope, and gramineae and members of the convolvulaceae family (commonly cynodon - *Cynodon intermedius*) in the back swamps (Figure 6.17).

Table 6.24 Vegetation diversity observed in agricultural land during the post-monsoon season.

Plant species				No. of species sampled in all quadrats					
Herbs:				Natural levee		Back slope		Back swamp	
English name	**Native name**	**Scientific name**	**Family name**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Phyla nodiflora	Bhui kaira	*Phylla nodiflora* (Linn.) Greene	Verbenaceae	50	20	80	35	10	5
Polygonum hydropiper	Bishkatali	*Ploygonum hydropiper L.*	Polygona	35	20	50	30	20	15
Hydrilla	Doal	*Hydrilla verticillata Linn.*	Hydrocharitacea	-	-	-	-	20	16
Cyprus	Deshi badain	*Cyprus verticillatra Linn*	Cyperaceae	20	12	40	24	14	8
Coriander	Dhania	*Coriandrum sativum* Linn.	Umbelliferae	30	-	40	30	-	-
Caugh Grass	Durba ghas	*Cynodon dactylon* Pers.	Gramineae	45	30	50	65	-	-
Paspalum	Gaiccha	*Paspalum conjugatum.Linn*	Gramineae	20	12	30	18	-	-
Wheat	Goam	*Triticum aestivum* Linn. (T.vulgare Linn.)	Gramineae	38	36	48	42	-	-
Kalakasunda	Kalakasunda	*Cassia sophera* linn.	Lauraceae	8	4	20	10	12	5
Portulaca	Lania	*Portulaca pilosa* Linn.	Portulacaceae	18	10	25	14	-	-
Vigna	Maskalai	*Vigna mungo* (Linn.)	Leguminosae	120	75	150	100	-	-
Bat lily	Moti munda	*Tacca Leavis* Roxb.	Taccaceae	4	2	8	4	-	-
Indian Spinach	Puisaak	*Basella alba* Linn.	Basellaceae	4	2	6	4	-	-
Alternanthera	Sachi Saak	*Alternathera sessilis* (Linn.) DC.	Amaranthaceae	-	-	12	6	16	10
Total				392	223	559	382	92	59
%				64	36	59	41	61	39
Shrubs:									
Sungrass	Chonghas	*Imperata arundinaceae*	Graminae	25	35	-	-	25	35
Green chili	Kacha morich	*Capsicum annum* Linn.	Solanaceae	20		25	16	20	-
Total				45	35	25	16	45	35
%				56	44	61	39	56	44

Table 6.25 Density, frequency and abundance of vegetation in agricultural land during the post-monsoon season.

Vegetation types	Total Number of species		Density (Plant/m^2)		Relative Density (%)		Frequency (%)		Relative Frequency (%)		Abundance	
	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Herbs	1043	664	104	66	61	39	90	60	60	40	104	83
Shrubs	115	86	12	9	57	43	50	40	56	44	14	9

Table 6.26 Family wise vegetation diversity in agricultural land during the post-monsoon season.

Sl. No.	Family name	Habit	Percentage of Occurrence	Order
1	Amaranthaceae	Herb	6	2
2	Basellaceae	Herb	6	2
3	Cyperaceae	Herb	6	2
4	Graminae	Shrub	28	1
5	Hydrocharitacea	Herb	6	2
6	Lauraceae	Herb	6	2
7	Leguminosae	Herb	6	2
8	Polygona	Herb	6	2
9	Portulacaceae	Herb	6	2
10	Solanaceae	Shrub	6	2
11	Taccaceae	Herb	6	2
12	Umbelliferae	Herb	6	2
13	Verbenaceae	Herb	6	2

Figure 6.18 further illustrates that gramineae species constituted the largest proportion of species (60%), with amaranthaceae (25%), convolvulaceae (10%) and Leguminosae (5%) making up the remainder of the plants sampled. The field study also showed sun grass (*Imperata arundinaceae, Imperata cylindrica)* and Saccharum *(Saccharam Spontaneum)* to be the major, deep-rooted vegetation species. They were not only widespread but also grew more or less perennially, acting as natural traps for coarse sediments throughout the flood season.

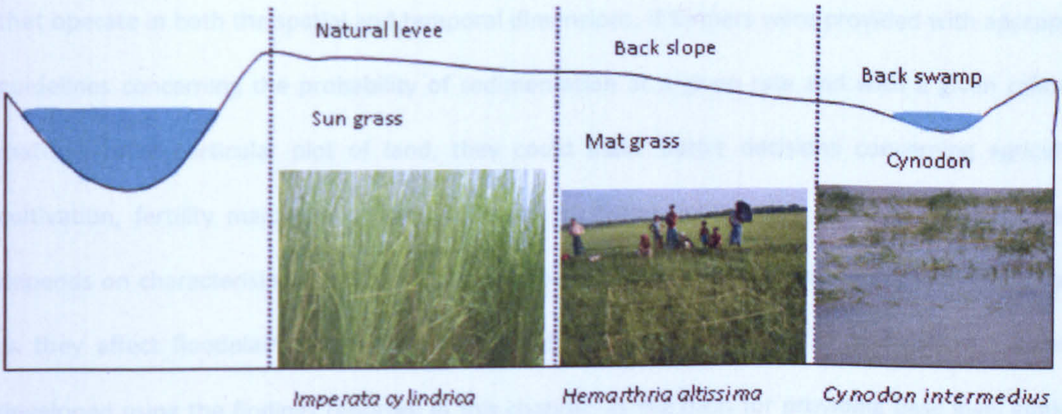


Figure 6.17 The common vegetation species over the floodplain

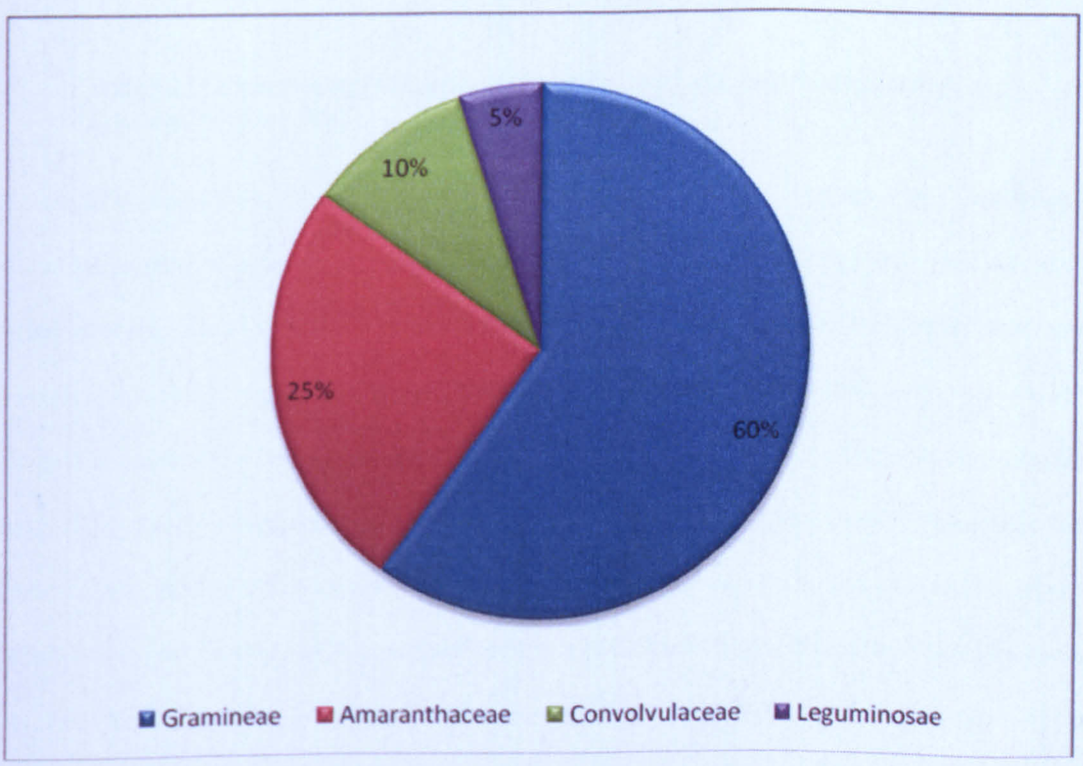


Figure 6.18 Distribution of vegetation species over the floodplain in the study area

6.4 Conclusion

These results provide a number of important insights concerning how floodplain sedimentation varies with floodplain topography and how it interacts with agricultural land use and vegetation. The results reported here demonstrate that floodplain sedimentation represents the cumulative outcome of complex interrelationships between the antecedent morphology of the floodplain, the prevailing fluvial process (depth, velocity and duration of flooding), agricultural land use and vegetation type that operate in both the spatial and temporal dimensions. If farmers were provided with appropriate guidelines concerning the probability of sedimentation at a given rate and with a given calibre of material on a particular plot of land, they could make better decisions concerning agricultural cultivation, fertility management, and sediment buffering, accordingly. Supplying such guidelines depends on characterising the interactions between physical processes and human decision making as they affect floodplain sedimentation. Towards this end, in Chapter 7, a Bayesian network is developed using the findings reported in this chapter, as the basis for providing base level guidance on optimising selection of the appropriate crop for a given plot of agricultural land.

CHAPTER 7 DEVELOPMENT OF A BAYESIAN DECISION SUPPORT SYSTEM

7.1 Introduction

This chapter describes the results of an investigation into farmers' vernacular knowledge in accounting for flooding and sedimentation when selecting which crop to cultivate on a given plot of land in the *Bara Bania* area of the *Manikganj* District within the Brahmaputra-Jamuna floodplain, Bangladesh. This is important because most farmers rely on their personal knowledge and understanding of flooding, sedimentation, and soil characteristics when making decisions concerning crop selection. It follows, therefore, that an investigation should be undertaken to determine whether farmers could make better decisions if they had better information concerning interactions between fluvial processes, sedimentation, vegetation, and land use. In fact, the implications of such an investigation extend beyond crop selection to farmers' decision making on land use more generally. In this investigation, a Bayesian Decision Support System (BDSS) was developed by using a combination of physical model (physical parameters) and Farmers' socio-economic model (socio-economic variables) to infer the probable outcomes of decisions concerning the use of a given plot of land for multiple crops in a year and so assist the farmer in selecting the optimal crop for that plot.

7.2 Rationale for combining Physical model and Farmers' socio-economic model in a Bayesian Network (BN)

The physical model includes the variables of landform, flood depth, flood duration, flow velocity, vegetation, sediment deposition thicknes, sediment types (% of sand, silt and clay) and the farmer socieoeconomic model variables are family size, farm size, market price of crops and farmer crop selection (number of agricultural crops; single, double, triple). Bangladeshi farmers are mostly engaged in subsistence farming, though many attempt to generate some income by selling surplus crops. It follows that farmers must consider the socioeconomic condition (family size, family food demand, farm size, and the market price of crops) when deciding which and how many crops to cultivate in a year. In this context, farmers' land use decision making is biased by traditional agents (i.e. cultural-food habits) and relies mostly on vernacular knowledge of the soil type. Hence, vernacular knowledge on soil type and agricultural crop selection is the key source of information to support land use decision-making, based on qualitative rather than quantitative assessment of the soil and related properties.

Farmers are also aware that their land is likely to be inundated by the monsoon flood, which provides river borne sediment, every year. Bangladesh governmental organizations are responsible for disseminating sediment related information to all farmers, although bureaucratic and technological constraints limit the reach of these organisations at village level. In practice, farmer's vernacular knowledge, which is based on long term farming experience, is usually also the basis for considering the type and amount of sediment that might be deposited on a plot of land annually. This traditional approach, which is based on the farmer's own (vernacular) knowledge, provides a reasonable basis for land use decision-making, but yields could be improved if farmers had access to scientific information, particularly concerning the type of sediment likely to be deposited on a plot in any given year.

Unfortunately, traditional approaches to decision making like those currently employed in the study area are unable to synthesise scientific data and vernacular knowledge. Hence, for progress to occur it will be necessary to find a new approach to land use decision-making. A wide range of agricultural decision-making models are available, but most are based on simple and/or multiple linear regression analyses; classical inferential models that do not permit the introduction of prior knowledge into the calculations. Conversely, a Bayesian Network (BN) offers a novel approach in handling the prior knowledge and integrating the different variables together to support reasoning in both directions through forward and backward propagation. Bayesian decision support tools can analyse complex problems, resolve controversies, and support future decision-making in an adaptive management framework.

Three main approaches are commonly employed when data mining to support decision making in environmental management: classical analysis, Exploratory Data Analysis (EDA) and Bayesian analysis. These approaches follow sequences of steps from problem identification to conclusion that are generally similar, but which differ in detail (Figure 7.1). Of these approaches, only a Bayesian network combines the prior distributions of modelled variables and observed data prior to analysing them jointly. This allows the researcher to make inferences and test assumptions concerning model parameters before drawing conclusions. These capabilities explain why Bayesian networks are being used increasingly to investigate environmental issues and inform adaptive management (Varis, *et al.*, 1990; Lee and Reiman, 1997; Varis, 1997; Reckhow, 1999; Marcot *et al.*, 2001; Borsuk *et al.*, 2004; Bromley *et al*, 2005; Uusitalo, 2007).

Kontkanen *et al.* (1997a) found that a Bayesian network could provide accurate predictions based on very small samples, a discovery supported by Myllymäki *et al.* (2002), who pointed out that BNs do not require a minimum number of samples and thus can analyse data sets that are small or incomplete. Steck and Tresp (1999) identified that BNs can also support structural learning based on their capability to combine prior knowledge with observed data to identify the most likely outcome of a set of input parameters.

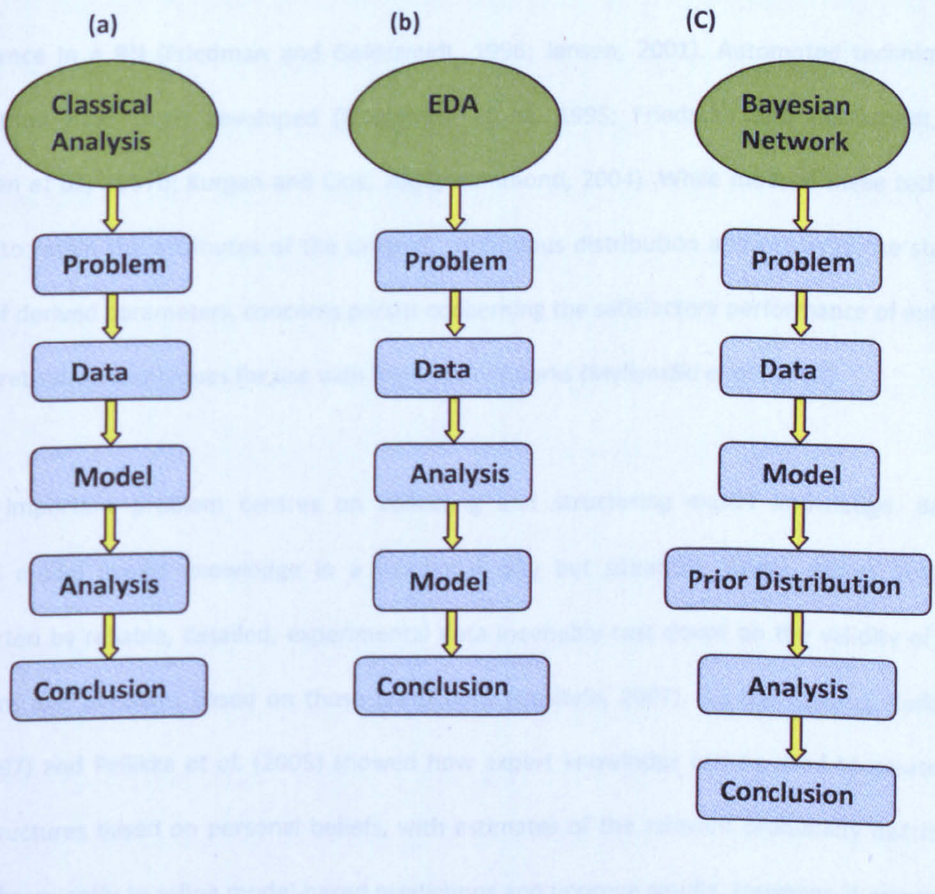


Figure 7.1 Sequences of steps in different analytical approaches; (a)Classical approach; (b) Exploratory Data analysis approach and (c) Bayesian network.

Kuikka *et al.* (1999) and Jensen (2001) recommended BNs due to their explicit treatment of uncertainty, which supports decision analysis based on first response and the capacity for computing predictions probabilistically within the problem domain. These examples serve to illustrate that Bayesian networks offer several advantages for decision support and analysis, including; consistent treatment of qualitative beliefs and observed data, smooth representation of variable properties, flexible applicability, a sound theoretical framework for handling expert knowledge, and clear semantic interpretation of the model parameters.

Notwithstanding the inferential power and potential for BNs to represent conditional probability distributions for a set of variables in a compact and simple way, there are inherent challenges to the use of Bayesian networks (Uusitalo, 2007). The most fundamental problem concerns representation of continuous data as being discrete. This arises because, in nature, most environmental parameters vary continuously, but BNs have more limited capacity to deal with continuous data compared to discrete data. As result, it may be necessary to discretise continuous data to obtain satisfactory performance in a BN (Friedman and Goldszmidt, 1996; Jensen, 2001). Automated techniques for discretisation have been developed (Dougherty *et al.,* 1995; Friedman and Goldszmidt, 1996; Kontkanen *et al.,* 1997b; Kurgan and Cios, 2001; Hammond, 2004). While most of these techniques attempt to retain the attributes of the original, continuous distribution and preserve the statistical validity of derived parameters, concerns persist concerning the satisfactory performance of automatic data discretisation techniques for use with Bayesian networks (Myllymäki *et al.*, 2002).

Another important problem centres on collecting and structuring expert knowledge. Bayesian networks model expert knowledge in a functional way but situations where expert beliefs are unsupported by reliable, detailed, experimental data inevitably cast doubt on the validity of a BN's predictions and decisions based on those predictions (Uusitalo, 2007). In this context, Kuikka and Varis (1997) and Pellikka *et al.* (2005) showed how expert knowledge can be used to create initial model structures based on personal beliefs, with estimates of the relevant probability distributions added subsequently to refine model-based predictions and improve results. However, it remains true that this approach integrates expert knowledge with synthetic probability distributions is unsatisfactory (Morgan and Henrion, 1990). This is the case because the primary principle of Bayesian network construction is that nodes or variables should be connected as an acyclic order. If either causal directions are changed or the wrong variables are chosen for inclusion in a net, this may distort the entire network and invalidate the result because acyclic nets do not support feedback loops that might otherwise compensate for errors in causality or the variables included (Jensen, 2001 and Uusitalo, 2007). The inevitable conclusion is that a Bayesian network is only as useful as the reliability of the prior knowledge upon which it is based and, hence, it is very important that the prior beliefs used in Bayesian inference processing are of high quality and fully describe the environmental system being modelled.

7.3 Overview of Bayesian Networks

A Bayesian network is a probabilistic, graphical model that represents a set of variables and their probabilistic independencies. Since the 1990s, a method of reasoning using probabilities, variously described as Bayesian Networks (BNs), Belief Networks (BNs), Knowledge Maps (KMs), Probabilistic Causal Networks (PCNs), Causal Networks (CNs), or Influence Diagrams (IDs), has become increasingly popular within the interface community dealing with probability and uncertainty. In the most general terms, these tools are annotated, directed graphs that represent the states of variables based on a set of conditional probability distributions. Pearl (1988) defined a Bayesian Network as a graphical representation, based on multivariate joint probability distributions. At the same time, a BN reflects the states of phenomena in a form of directed acyclic and probabilistic graphical model, which used to establish the causal (cause – effect) relationship among the variables (Jensen, 1996).

Fundamentally, the Bayesian Network is based on an approach to probability theory developed by Thomas Bayes, an 18th Century English clergyman. In the last decade, there has been a great deal of research focused on the problem of learning BNs from data (Buntine, 1996; Heckerman, 1998) with the technique initially applied successfully in medical sciences and the artificial intelligence arena (Charniak, 1991; Heckerman *et al.,* 1995; Jensen, 1996 and Pearl, 1998). Subsequently, there has been increased interest in probabilistic, graphical models in the environmental sciences and natural resource management. The advantage of Bayesian networks compared to other models is that they offer alternatives based on reasoning analysis. In this context, Varis (1995) first generalised and rearranged the mathematical framework to analyse the environmental attributes of an area (Castelletti and Soncini-Sessa, 2007). More recently, an increasing trend has emerged for BNs to be used to investigate environmental phenomena in general and ecological and catchment management issues in particular (Kuikka and Varis, 1997; Kuikka *et al.*, 1999; Ames and Neilson, 2001; and Borsuk *et al.*, 2001; Little *et al.*, 2004). These researchers focused on using Bayesian networks to integrate probabilistic information derived from data sets dealing primarily with water allocation and pollution problems. Similarly, Borsuk *et al.* (2001, 2004) used BNs to integrate processes-based, multivariate regression relations with expert opinion on river eutrophication to make probabilistic predictions of policy relevant, ecosystem attributes that accounted for feedback relationships and model validation problems.

Varis and Lahtela (2002) used BNs to predict the basin-wide impacts of different water management policies on different user groups in the Senegal River Basin through scenario analysis. Their research posed particular challenges to inferential analysis due to the large number of variables (45) and causal linkages (840) involved. This is the case because a large number of model nodes do not automatically lead to higher uncertainty and thus network's prediction may lead to invalid evaluations. Castelletti and Soncini-Sessa (2007) used Bayesian networks and participatory modelling in water resource management. This research mainly discussed integration of Bayesian networks with other decision models and examined the potential for using BNs in integrated planning. Barton *et al.* (2008) used a BN as a tool to monitor integrated river basin management in Norway. They report a number of features generic to Bayesian networks that are well suited to integrating the results of diverse models for the purpose of river basin management.

Mount and Stott (2008) applied a discrete Bayesian network to investigate hydrological processes based on measured suspended sediment concentrations in an alpine, pro-glacial stream. They attempted to model the potential impacts of increased air temperatures on suspended sediment concentrations and found the results of their Bayesian networks to be consistent with conventional regression analyses. They described the BN as a novel approach to modelling suspended sediment concentrations in different fluvial environments and renamed the Bayesian network as the 'Bayesian paradigm'. They concluded that a Bayesian paradigm offers a more versatile framework for modelling hydrological processes than any traditional, deterministic approach.

The potential of Bayesian methods in relation to risk and vulnerability assessment has been investigated in a range of contexts including; land sliding (Lee and Choi, 2004), catchment management (Ames *et al.*, 2005), and land use change (Stassopoulou *et al.*, 1998; Guisan and Zimmermann, 2000; Prato, 2000; Marcot *et al.*, 2001; Aalders, 2008). Some of these researchers have also explained the use of participatory modelling methods alongside Bayesian Networks (Bacon *et al.*, 2002; Lynam *et al.*, 2002; Cain *et al.*, 2003). Although most of these researchers explain how Bayesian networks can deal with multi-dimensional phenomena in predicting causal relationships between variables, the technique remains under-used within the Geographical community, especially given its capacity for integrating human and physical variables when making inferences to support decision-making.

Based on this brief review, it may be concluded that Bayesian Networks (BNs) represent a flexible alternative to deterministic decision support frameworks, capable of integrating quantitative data with beliefs based on expert and vernacular knowledge. Hence, it was decided to develop Bayesian Decision Network (BDN) as a decision support tool for farmers needing to improve their land use decisions.

7.3.1 Principles of structuring Bayesian networks

Bayesian networks provide a framework for prediction of prior probabilities and conditional probabilities following the Bayes' rule;

Bayes' Rule

The fundamental rule of probability calculus is:

$$P(A|B)P(B) = P(A,B) \qquad (7.1)$$

where, $P(A,B)$ = probability of the joint event $(A \cap B)$. Probabilities of event are often conditioned by a context, C, in which case:

$$P(A|B,C)P(B|C) = P(A,B|C) \tag{7.2}$$

From (6.1) it follows that $P(A|B)P(B) = P(B|A)(A)$ and this yields the well-known Bayes' rule:

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} \tag{7.3}$$

In this way, Bayes' theorem offers a mathematical basis from which to calculate the conditional probability of any combination of the events.

If it is desired to add more variables, the Bayes' rule conditioned on C reads:

$$P(B|A,C) = \frac{P(A|B,C)P(B|C)}{P(A|C)} \tag{7.4}$$

Thus, the Bayes' rule provides the basis for causal and inferential, probabilistic modelling and lies at the root of all Bayesian Networks.

The Bayesian network itself consists of a set of nodes, which are connected by directed links in an acyclic order. Nodes represent the distribution of possible states of the random variables of observable features, with the links between them representing conditional dependences based on causal links between the nodes. Hence, nodes can be classified as being either a parent or a child, relative to the other nodes in the network (Figure 7.2).

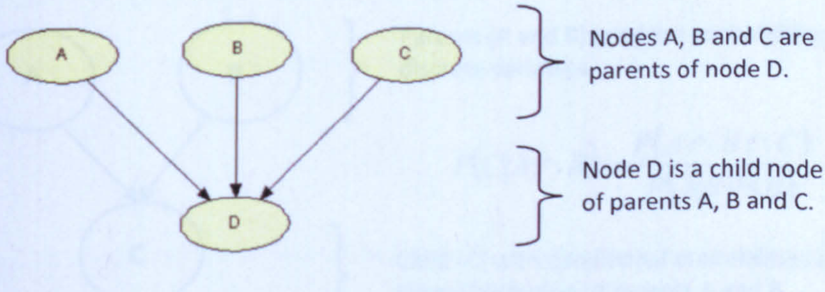


Figure 7.2 Parent and child structure of nodes in a very simple Bayesian network

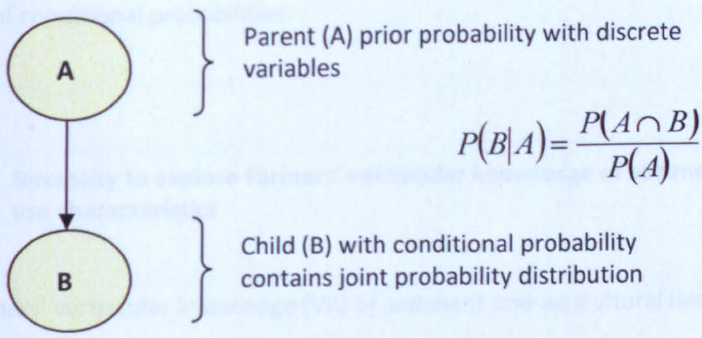
Here, parental nodes (A, B and C) are considered as prior probabilities because they are not conditionally dependent. However, the child node (D) is the ultimate effect of nodes A, B, and C and it is, therefore, conditionally dependent on each of the parental nodes. Hence, according to Bayes' theorem the joint probability distribution for the child node is defined by:

$$P(X_i,..........X_n) = \prod_{i=1}^{n} P(X_i | parents(X_i)) \qquad (7.5)$$

where, X = a discrete random variable.

It is important to note that every node in the network must be defined in the probability table. Those nodes that act as parents and are defined as prior probabilities with discrete variable states, while child nodes are defined as conditional probabilities that result from the joint probability distribution (Mount and Stott, 2008).

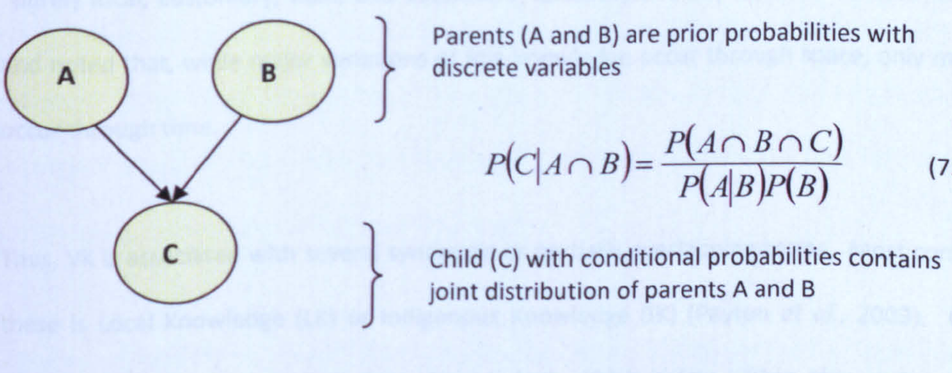
For a child node with a single parent (Figure 7.3), the conditional probability can be calculated as;



$$P(B|A) = \frac{P(A \cap B)}{P(A)} \qquad (7.6)$$

Figure 7.3 single parents Bayesian net with prior and joint probability distribution

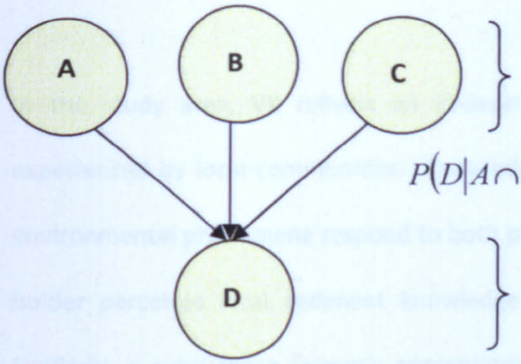
Similarly, for a child node with two parents (Figure 7.4);



$$P(C|A \cap B) = \frac{P(A \cap B \cap C)}{P(A|B)P(B)} \qquad (7.7)$$

Figure 7.4 Two parents Bayesian net with prior and joint probability distribution

For a child node with three parents (Figure 7.5);



$$P(D|A\cap B\cap C)=\frac{P(A\cap B\cap C\cap D)}{P(A|B\cap C)\times P(B|C)\times P(C)} \tag{7.8}$$

Figure 7.5 Three parent, Bayesian net with prior and joint probability distribution

In this way, as many random variables as required can be accounted for in the Bayesian network. Each parental node will forward its prior probability to its child node in a convergent way and without any conditional probabilities, but a child node always requires a joint probability distribution with a set of conditional probabilities.

7.4 Necessity to explore Farmers' vernacular knowledge of sedimentation and agricultural land use characteristics

Farmers' vernacular knowledge (VK) of sediment and agricultural land use can be defined as a kind of native knowledge that is commonly held and practised by the community. This pertains to local institutionalization of knowledge that has been gained through long experience and transferred from generation to generation (Winklerprins, 1999; Braimoh, 2002). Jackson (1984:85) defined VK as, "purely local, customary, fluid, and adaptive". Glassie (1968:33) equated VK with 'folk knowledge' and noted that, while major variations of folk knowledge occur through space, only minor variations occur through time.

Thus, VK is associated with several synonyms or partially overlapping terms. Most common amongst these is Local Knowledge (LK) or Indigenous Knowledge (IK) (Payton *et al.*, 2003). Grenier (1988) defined local knowledge as 'unique knowledge', which exists within the environment and has developed indigenously to the specific conditions of that environment. It is experientially rooted in place and transmitted orally or by practice (Ellen and Harris, 2000).

In the study area, VK reflects an in-depth knowledge of local environmental parameters, as experienced by local communities. Knowledge of and perceptions about sedimentation and other environmental phenomena respond to both physical and social variability. For example, a small farm holder perceives local sediment knowledge more indigenously than does a large farm owner. Similarly, a subsistence farmer's perceptions of sedimentation vary from those of a commercial farmer, particularly with respect to their education and ability to synthesize objective, scientific information. Subsistence farmers operate at very local spatial and temporal scales acquiring and utilising knowledge that is specific to their own environment and taking decisions on agricultural land use which may be ignorant of wider knowledge expressed through generalised scientific principles (Winklerprins, 1999). Although scientific knowledge, based on controlled experiments, may appear 'better', it is important for any plan to improve practice to function optimally, to integrate the knowledge of local people (based on their own experience, intimate understanding of their locality and personal development through trial and error), in a participatory process.

For example, local soil knowledge has implications for sustainable land use management because local specificity plays a substantial role in improving agricultural and natural resource management (DeWalt, 1994; Pretty, 1995; Winklerprins, 1999). It has been demonstrated that farmers who directly relate their agricultural activities to their local environmental knowledge act as a good land managers (Blaikie and Brookfield, 1987; Chambers, 1990). More specifically, farmer's vernacular knowledge has been shown to provide the basis for sound agricultural decision making in developing nations (Warren, 1992; White *et al.*, 2000). Therefore, the study of local soil knowledge has received increasing attention by researchers seeking to promote sustainable land management through optimum agricultural land use decision making.

This brief review of the relevant literature has highlighted the importance of VK to land use decision making, particularly in developing nations. Many studies have been performed in African nations including Niger (Taylor-Powell *et al.*, 1991; Sterk and Haigis, 1998); Mali (Ayers,1995); Nigeria (Osunade, 1988; 1994; Warren, 1992; Philips-Howard and Binns, 1995; Ishida, 1998); Zimbabwe (Nyamapfene, 1983; Mavedzenge *et al.*, 1999); Senegal (Tabor, 1990); Ethiopia (Corbeels *et al.*, 2000); Rwanda (Habarurema and Steiner, 1997); and Kenya (Mairura *et al.*, 2007). Studies outside Africa include; Peru (Furbee, 1989; Sandor and Furbee, 1996); the Amazon Basin (Hecht, 1990; De Queiroz and Norton, 1992); Cambodia (White *et al.*, 2000); and Bangladesh (Payton *et al.*, 2003; Ali, 2003, 2007; Rahman, 2005).

In disciplinary terms, research has been performed by geographers (e.g. Bradley, 1983; Osunade, 1988; Hetch, 1980; Dunning, 1990; Carney, 1991; Ryder, 1994; Zimmerer, 1994; and Winklerprins, 1999) with a focus on spatial and temporal variabilities in local soil knowledge. Anthropologists (e.g. Ollier *et al.*, 1971; Richards, 1985; Furbee, 1989; Guillet, 1989; Wilshusen and Stone, 1990) have concentrated on ethnographical studies. Development specialists (e.g. Brouwers, 1993; Tabor, 1992; Tabor and Hutchinson, 1994) and soil scientists (Pawluk *et al.*, 1992; Sandor and Furbee, 1996; Kundiri *et al.*, 1997; Habarurema and Steiner, 1997; Sillitoe, 1998; Gobin *et al.*, 1998, 2000) have investigated the potential of indigenous knowledge to be better applied to land management.

Most of these investigations focus on local knowledge about soil and environment, and how widening possession and improving the sophistication of this knowledge can aid in maintaining soil quality to support sustainable land use.

Talawar and Rhoades (1998) and Winklerprins (1999) present reviews of research on local soil knowledge in sustainable land management that identify three categories of investigation; ethnographies, nomenclature studies and utilitarian studies. Ethnographic studies describe the ways that different groups of people perceive and describe the soil. This involves listing the criteria locally used to characterise the soil and describing how these criteria can be used to inform land use decisions. Although this is a valid and valuable approach, its utility is limited due to the lack of a scientific classification of the soil knowledge against which to compare the findings of the ethnographer.

Nomenclature studies address the ways that local people name and classify the soils in their area into groups based on their own knowledge and experience. These types of indigenous soil classification may be correlated with standardised soil classification systems, like that of the United States Department of Agriculture (USDA) Soil Taxonomy System, to test the validity of local soil knowledge.

Winklerprins (1999) identified a third type of research study as utilitarian, meaning that it progresses from the descriptive and correlative approaches described above toward incorporation local soil knowledge into development issues and which involves knowledge transfer to land agricultural scientists and officials. In this context, Thrupp (1989) and Chambers (1990) emphasised the importance of the 'farmer-first' research approach, which provides opportunities for dialogue between farmers and agricultural scientists. This involves the two-way exchange of knowledge, where scientists learn from farmers as well as *vice versa*. This approach is more effective because it engages local people and respects their knowledge, which can be combined with science-based knowledge to guide farmers in making decisions on land planning and use.

Bangladesh is an agrarian country and about 80% of its population are engaged in agriculture. It therefore has a huge reservoir of indigenous, agricultural experience and knowledge, acquired over hundreds of years of inter-generational interactions and at scales ranging from the village to the national (Payton *et al.*, 2003; Ali, 2003, 2007; Rahman, 2005).

Although social scientists have investigated various aspects of the body of local knowledge in Bangladesh, most studies fall into the category of ethnographic surveys, rather than being utilitarian in their approach. In essence, this vast array of knowledge has been largely unexplored and even unrecorded. Further, it is widely recognised that the relevant sectors of the Bangladeshi government are dysfunctional due to being overly bureaucratic and centralised. As a result, poor farmers and small plot holders in rural areas mostly rely on their own knowledge and locally available support they can obtain easily from relatives and neighbours and, thus, they live very much from year to year, with little or no longer-term planning or development. Consequently, it is difficult to find a meaningful starting point when seeking to exploit local knowledge in developing an academic, doctoral study of the potential for science to improve agricultural decision-making.

Recently, however, development planners have taken an increased interest in the vernacular knowledge of local farmers. This stems from having realized that VK can serve as a catalyst for much-desired agricultural development. In particular, farmers' VK can be a valuable tool in enabling soil-related, agricultural technology transfer that is badly needed in the flood prone regions of Bangladesh. Although farmers' local knowledge stresses traditional approaches and promotes low-technology methods, there is evidence that it has to date proved a more environmentally sound and acceptable basis for the adaptation of agricultural innovation than high-technology methods introduced from the West (Tabor, 1990; Chokor and Odemerho, 1994; Winklerprins, 1999; Sandor and Furbee 1996).

The conclusion to be drawn from this review is that the vernacular knowledge held by Bangladeshi farmers has not to date been deeply researched with the aim of supporting improved agricultural decision-making. Given the pressure on farmers to increase productivity to meet the food needs of a growing population, it is imperative for this gap in understanding to be addressed as a matter of urgency.

7.5 Data and methods used in this study

The study area provides a suitable location for an investigation of farmers' VK, decision making as it is flood prone, and 95% of the working population are associated with agriculture. The main factors affecting agricultural land use in the area are the spatial and inter-annual flood variability, the associated sediment dynamics and soil properties, the farmers' VK concerning the potential risks and benefits of flooding, and the prevailing socio-economic conditions (which affect the farmers' capacity to apply their VK through taking decisions on cropping and land use). To gather the data necessary to elucidate these factors, a systematic field study was performed in 2007 and 2008. Information related to the farmers' vernacular knowledge in accounting for sediment was obtained through a semi-structured questionnaire survey. Further, unstructured, observational information was collected to support some of the questionnaire results. As described in the subsequent sections in this chapter field surveys were carried out during the summer monsoons in 2007 and 2008 using a 'mixed method approach'. The social and behavioural information gathered through this survey was subsequently combined with data on flood hydraulics (floodwater velocity, depth and duration), vegetation (type, frequency), and sediment dynamics (accumulation rate, particle size characteristics) in developing and testing a Bayesian Network (BN).

7.5.1 Data collection of farmers knowledge on sediment counting and agricultural crop selection

As outlined previously, based on a careful consideration of the research questions, the nature of the data needed for the analysis and prevailing conditions in the research field, it was evident that a combination of qualitative and quantitative approaches would be required. It was recognised that the qualitative data required could best be obtained through interviews, while the quantitative data would best be elicited by means of questionnaires. Furthermore, it was determined that the data required that was physically observable could be gathered through first hand, field inspection and observation. There was also available a range of published information, including academic publications and newspaper articles, that could yield data relevant to the study area. The techniques selected for gathering data therefore involved semi-structured questionnaires interviews, open-ended questionnaires, formal interviews, field observation, photography and documentary analysis.

7.5.1.1 Selection of the respondents for the study

According to the BBS census of 2001, there were 1741 people resident in the Bara Bania study area over 10 years of age. These were categorised by main activity as; not working (408), looking for work (21), household workers (649), agriculture (456), small cottage agriculture industry (1), transportation (7), business (56), services (4), and other employment (139). The census indicates that 91 out of 544 households were actively engaged in agriculture. In this study, a total of 50 respondents were (Appendix-C) interviewed each year in 2007 and 2008. 40 respondents were landowners in areas around the sediment sampling sites who were both directly and indirectly involved in agriculture, while the other 10 were key informants: mainly retired farmers with long experience in agriculture. The same respondents were interviewed in both years, allowing direct comparison of the farmers' perceptions and decision making during an extreme and a normal flood event. Thus, a total 100 interviews were conducted in two years.

The sample size was selected first and then the confidence interval was calculated. The true percentage of the sample population is between 37% and 55% at the 95% significance level. Details calculation is presented in (Appendix-C). The sample size 100 was acceptable because it was considered to represent the sediment sampling sites (40) that is 80 in two years and 20 key informants (10 each year).

People engaged in farming, the village leaders, and retired farmers, and agricultural related service men were considered to select the key informants (Table 7.1). These people were considered key informants with respect to obtaining reliable information on flooding, sedimentation, vegetation and agricultural cropping decision making in the study area.

Table 7.1 Key informant groups in the investigation of stakeholder perceptions of floodplain inundation, sedimentation, vegetation and agriculture

Category of key informant	Criteria of selection
Farmers	• Directly involved in agricultural decision making • Agricultural labourer • Experienced, retired farmer
Village leader	• Land owner farming land he owns himself Land owner who doesn't farm himself but who still determines land use
Services	• School teachers who own land and teach on agriculture although they don't practice agriculture themselves • NGO workers who advise on agriculture • Government agricultural extension workers operating at field level

7.5.1.2 Questionnaire development, testing, deployment, reliability and validity

Questionnaires are widely used in social science research to gather primary data concerning people's perceptions, behaviours, attitudes, opinions and awareness of specific issues. This is the case largely because questionnaires are generally found to be time and resource efficient compared to other possible techniques (Bryman, 2004).

A questionnaire was developed to specifically to address the objective of this part of the study, which was to investigate farmers' perceptions of the floodplain, sediment processes, the role of vegetation in affecting sediment accumulation, the implications for agricultural use of floodplain land and the resulting floodplain environment (Appendix-A). The questionnaire was therefore divided into four main parts. The first part established the demographic and socioeconomic circumstances of the respondent. Parts 2, 3 and 4 dealt with his or her perceptions of the floodplain and sedimentation (including vegetation effects); agricultural systems and crop selection; and the floodplain environment, respectively.

As the respondents mostly are illiterate therefore, interviews were conducted in person to ensure that the results were reliable and unbiased. Adequate preparations had to be taken prior to meeting the interviewees. For this purpose, I followed the Bryman's (2004) advice on interviewing; developing interview guidance based on the research questions; avoiding complex, double-barrelled or multi-barrelled questions; identifying potential respondents from the population; selecting the mode of recording the interview (note-taking and tape-recording); obtaining the necessary permissions from interviewees, and; arranging suitable times and places for the interviews to take place.

The interview questions were pilot-tested with a few farmers in the study area to check that the questions were clear and determine whether they produced answers relevant to the research questions. The pilot-testing revealed some deficiencies and the questions in the questionnaire were modified in ways appropriate for the study. In this way, the utility, validity and reliability of the questionnaires were improved. Once the content of the questionnaire had been finalised, the research team (myself plus two field assistants), administered the questionnaire. Some sub-sections were answered by all respondents, but others were specific to farmers and non-farmers. The questionnaire included some open-ended questions as well as the quantitative, closed questions. The closed questions required the respondent to choose from a number of possible responses, while the open-ended questions provided the opportunity for them to construct their own answers. Those respondents who were literate filled in the questionnaires themselves while the answers of those who were illiterate (mostly farmers) were written down for them by members of the research team. An advantage of the semi-structured questionnaire was that, while the closed-ended questions made the questionnaire easy to complete, the open-ended questions provided the opportunity for respondents to provide detailed, personal information based on their experience of the issues being investigated.

Once completed, the interview data were checked to assess their validity, particular attention being paid to identifying any contradictions or inconsistencies in the answers. These checks were completed immediately following completion of the survey and prior to tabulating the survey data. Where necessary, responses were checked with the interviewees to resolve any confused or anomalous answers. Moreover, cross-checking was performed using secondary documentation and photographic analysis. It is relevant to mention here that I was myself born in a village that is a flood-prone area of Bangladesh, being close to the *Arial Khan River* - a major distributary of *Padma River*. I lived in the village until I started high school, sometimes helping my grandfather with agricultural work. My familiarity with the challenges of living and working in a flood prone, rural area made me something of an insider and gave me the insight necessary to understand and interpret the farmers' views and opinions. My personal insight and experience proved extremely useful in checking the validity and reliability of the interview data.

Prior to undertaking research that involved interviews I obtained the cooperation of the relevant village leaders and school teacher to get all of the respondents together. I then introduced myself (as a faculty member, Department of Geography and Environment, Jahangirnagar University, Dhaka, Bangladesh), and explained that I was presently performing advanced research in pursuit of a PhD in the UK). I informed the respondents of my position and the nature of my research in order to make them aware of the significance and potential value of the research. I also assured them that the findings of my study would be fed back to them, to help them to make better decisions on cropping and land management. I did this so that they would realise that they and their communities might benefit from the research outcomes and so motivate them to consider their answers carefully and give me the best information they could. This preparation appeared to have been successful in that most respondents co-operated fully and without any hesitation. However, I had to pay cash incentives to some farmers and agricultural workers/labourers because it was necessary to interview them during working hours (as this led to a loss of income on their parts).

Ethical issues are unavoidable in this type of survey and the relevant steps were taken to inform respondents of the purpose of the research, obtain the necessary consents, secure access to study and sampling sites and assure the respondents regarding confidentiality and anonymity. I addressed these ethical issues by taking time to talk to respondents at length, explaining in detail the nature of their roles in the work and in doing so, I obtained the confidence and full cooperation of respondents from all levels of society. This was aided by gaining the support of village leaders. Confidentiality and anonymity were maintained throughout and I was careful never to disclose anyone's information to other respondents.

7.5.1.3 Questionnaire tabulation

All completed questionnaires were coded in a spreadsheet to produce quantitative information. Coding was performed carefully to ensure homogeneity and minimize any bias. Wherever dissimilarities were noticed, the information was checked against the interviews and unstructured observations. In 10 cases, this led to interviews being repeated to resolve issues that arose during coding.

Open-ended questions were coded according to the number of responses in the interviews and interpreted as percentages of total responses, while closed questions were interpreted as frequencies. The coded data was analyses using SPSS (Statistical Package for Social Science). Conditional probability tables (CPTs) were calculated based on the frequencies of specific variables describing farmer's VK concerning sediment and land use decision-making. These CPTs were then used in the Bayesian Network developed to predict land use decisions.

7.5.2 Hydrological, vegetation and sediment data

Hydrological data define inundation depth, flow velocity, duration and the landforms types of the monitoring site during monsoons of 2007 and 2008. The procedures used to collect the data were described in Chapter 4, Section 4.4.2. Vegetation data define the type and relative frequency of plants sampled in an area, as described in Chapter 6, Section 6.3.2. Monitoring of floodplain sediment accumulation was described in Chapter 4, Section 4.4.3 with the PSA outlined in Section 4.4.4. This quantitative information on floodplain hydrology, sedimentation, and vegetation was transformed into relative frequency then used to calculate conditional probability tables (CPTs) using Bayes' formula. These CPTs were then used in the Bayesian Network as appropriate to each of the nodes, to make probabilistic predictions of optimum land use decisions based on the hydrological, sediment and vegetative characteristics of a plot.

7.5.3 Conditional probability calculation

A number of methods are available to calculate the conditional probabilities. Traditionally, these include; calculation of relative frequencies in the relevant datasets, use of an existing table of sample means and measures of variation, statistical models for means and variations, mathematical relations, and expert knowledge.

In cases requiring the combination of multiple nodes or variables, equation 6.8 and the associated equations may be used to calculate the conditional probabilities. It was explained earlier that each node might be regarded as either a parent or a child. Conditional probabilities are calculated for nodes that are linked to a parent, with marginal probabilities calculated for nodes that do not have a parent node.

In this study, the relative frequencies technique was used to calculate marginal probabilities for the variable 'landforms' and conditional probabilities for the variables, 'flood depth', 'flood duration', 'velocity', 'vegetation frequency', 'sediment deposition' and 'sediment grain size'. This is a simple way of estimating probabilities based on the relative occurrences of each state of the influenced (child) node for each possible combination of parent nodes in the observed data. Once all the relative frequencies had been calculated, pivot tables were constructed in Microsoft Excel. When the relative frequency was known for each of the states, the Bayes formulae (equations 6.1 to 6.8) were applied using a chain rule arrangement (Mount and Stott, 2008) to calculate the marginal or conditional probabilities for each node in turn.

The next task was to calculate conditional probabilities for the farmers' decisions on the number of agricultural crops they would plant in event that either sand, silt or clay particles were deposited on a plot during the monsoon flood. The results of the questionnaire survey were used to estimate relative frequencies for decisions and then conditional probabilities were calculated using the Bayes' rule and formulae. It should be recognised that the data generated by the survey are not scientifically objective but stem from vernacular knowledge (that is the beliefs of the farmers) that essentially produces subjective rules. For example, some farmers believe that, if a catastrophic flood occurs, the sediment that accumulates on their plot may be thicker and coarser than usual, leading them to make their crop selection decision based on the type of flood (*barsha* or *bonna*). Hence, it is necessary to measure the actual amount and calibre of sediment type deposited during flood and then relates this to the potential benefits/risks for different numbers and types of agricultural crop.

In this context, farmers' vernacular knowledge, based on long-term agricultural practices and experience, is being used as a form of expert knowledge. Decision-making involves not only selecting the optimal crop type, but also the planting strategy, depending on whether it is predicted that the plot will be suitable for single, double or triple cropping in the following year, or must be left fallow due to sand deposition. It should be recalled that in developing the conditional probabilities for decision nodes in the influence diagram (created by adding decision and utility nodes to the Bayesian Network), the results drawn on stemed are derived from the expert knowledge of both farmers and other key informants.

7.5.4 Implementation using Hugin Software

A large number of software packages are available to construct the Bayesian networks on desktop computers with different operating systems. Each has its own strengths and limitations and differs in of source codes and language, application program interface (API), types of nodes, number of nodes and states, graphical user interface (GUI), whether an influence diagram is supported (includes utility and decision nodes), graph types and cost.

Due to its suitability for environmental applications, Hugin software is widely used in environmental research. Hugin is capable of handling up to 50 states; either in the form of 5 variables with 10 states, or 25 variables with 2 states each and deals with discrete data. It supports pure BNs and influence diagrams. Hugin offers a learning structure with a conditional independency test and deals only with directed graphs. Having carefully considered the capabilities, relative strengths and limitations, Hugin was found to be more user-friendly and to have advantages in the areas of data insertion and compilation, structuring the model and graphing the outcomes.

Hence, the Bayesian networks presented here have been developed in the Hugin® graphical user interface (GUI) (version 6.9/2007) environment (Jensen, 1996). This interactive tool employs the facilities of the Hugin Decision Engine. It allows construction of models that can be used in many environmental applications. Practical implementation of the BNs was performed in a series of sequential steps through structuring the network, populating the conditional probability table and compilation of the networks. Finally, the results were obtained by forward and backward propagation of the nodes.

7.5.5 Model structure

Figure 7.6 presents the overall model structure. The chance nodes indicate the variables and arrows show the causal links, the values of which are specified based on the correlation coefficients between the variables concerned, which are listed in Tables 7.2 as conditional dependencies. These correlations are based on the results of the field observations and surveys. Broadly, this model comprises of two sub-models; a physical sub-model that makes probabilistic predictions of sediment deposition thickness and grain size, and a socio-economic sub-model that predicts the farmer's decision on which agricultural crops to plant for a given plot of land.

The variables influencing sediment deposition and grain size are the flood depth, flood duration, and flood flow velocity each of which has a significant, positive correlation with landform. There is considerable variability existing within the landform, in terms of relief, height and location relative to the river. Hence, just three types of landforms have been specified, with the landform variable being used as the proxy variable of the distance of the plot from the river. The landform categories are; natural levee, back slope, or back swamp, representing distances from the river that are short, medium or long, respectively.

Vegetation density also influences sediment thickness and calibre though a significant, inverse correlation with landform. Therefore, landform is considered a parent node, with flood depth, flood duration, flood flow velocity and vegetation density being its child nodes. Vegetation density also influences flood flow velocity. Hence, flood flow velocity is the child of two parental nodes; landform and vegetation. The same approach is used to calculate the probability of sediment deposition thickness as the child node of flood depth, flood duration, flood flow velocity and vegetation density. Similarly, deposited sediment particle size distribution (grain size) is the child node of deposition thickness, flood depth, flood duration, flood flow velocity, vegetation density, and sediment deposition thickness.

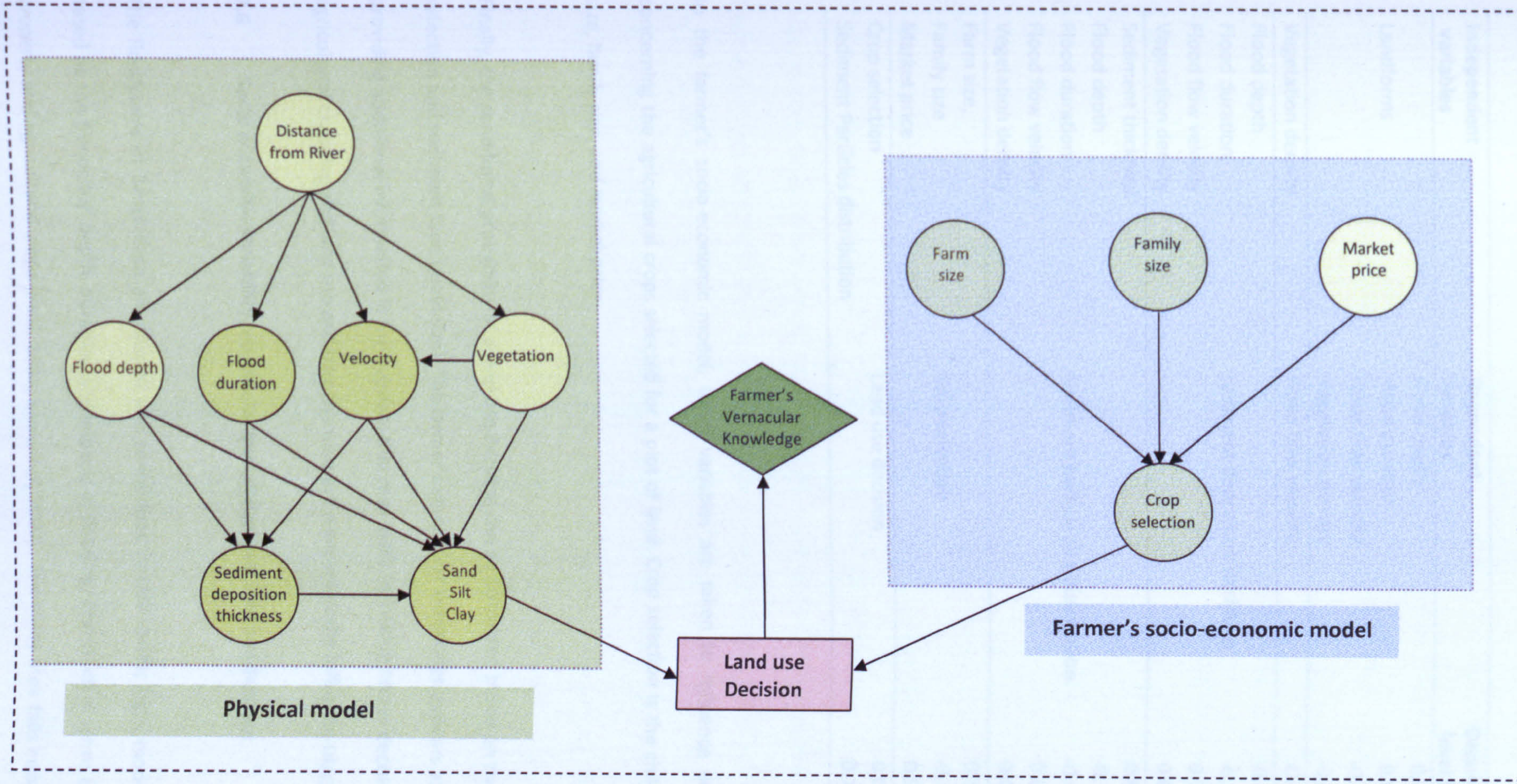


Figure 7.6 Overall model structure of the Bayesian network [Circle = chance nodes, diamond = utility node, rectangle = decision node]

Table 7.2 Correlation coefficients between the variables

Independent variables	Dependent variables	Dependency level (±r)
Landforms	Flood depth	0.70
	Flood duration	0.65
	Flood flow velocity	-0.70
	Vegetation density	-0.55
Vegetation density	Flood flow velocity	-0.68
Flood depth	Sediment deposition thickness	-0.65
Flood duration		-0.50
Flood flow velocity		0.74
Vegetation density		0.69
Sediment thickness	Sediment particle size distribution	0.80
Flood depth		-0.75
Flood duration		-0.65
Flood flow velocity		0.60
Vegetation density		0.65
Farm size,	Crop selection	0.85
Family size		-0.70
Market price		0.95
Crop selection	Land use decision	0.60
Sediment Particles distribution		0.70

In the farmer's socio-economic model, three variables are taken to influence decision making concerning the agricultural crops selected for a plot of land. Crop selection is the child node of farm size, family size, and market price.

Finally, the conditional probability of a land use decision can be calculated based on the farmer's crop selection and sediment type (grain size). The farmer's vernacular knowledge appears as a utility node, providing additional information in the network that may assist in making better decisions concerning agricultural cropping and land use and thus this network is known as the Influence Diagram.

7.6 Socio economic variability, vernacular knowledge, and land use decision

The floodplains of Bangladesh are divided into three-flood hazard zones; high, moderate and low, based on the frequency, depth, duration, and impacts of flooding, expressed in terms of losses of life, property and agricultural crops (Paul, 1984; Brammer, 2000). The study area falls into the high flood hazard zone. The dependence of the local population on subsistence and commercial agriculture, coupled with the vulnerability of their land to flooding, mean that farmers face an annual dilemma in selecting the right crop for their particular plot of land, based on their interpretation of the flooding situation. Given the importance of agriculture, the factors that affect these decisions are of fundamental importance to crop productivity and the lives of the people. The succeeding sections present and discuss the results of investigations performed to identify the socio-economic variables that influence the outcomes and how vernacular and scientific knowledge are applied when making those decisions.

7.6.1 Respondents' characteristics

Figure 7.7 and Table 7.3 list respondents' professions and ages. Almost 85% of them are directly engaged in agriculture, with 32% farming their own land, 9% engaging labours to farm their land for them, 15% renting out their land for others to farm, and 5% farming cash crops. The remaining respondents included retired farmers, a schoolteacher, village leader, and a governmental agricultural extension worker, who, although they are not directly involved in agriculture, may still be considered key informants. Respondents ranged in age from 31 to 60 years, with the majority of active farmers being between 31 and 50 years old. This establishes that the respondents had a considerable body of personal experience. Table 7.4 and Figure 7.8 show the respondents' literacy levels. The largest group (38%) were illiterate and a further 19% could only sign their name. Only 16% had completed secondary school and 11% higher secondary school. Just 4% had an undergraduate education and 1% a post graduate degree.

The findings indicate that the 57% respondents who farm the land themselves lacked any form of education. Hence, they are unable to read about advances in agricultural science and must rely on traditional methods. 43% of respondents did not actually farm themselves but employed others to do so on their behalf. These individuals worked in other professions including local administration (*union parisad*), teaching, and permanent or seasonal business. The vast majority (98%) of the population belonged to families that have lived in the area for generations and only 2% had migrated into the area within the last 10 years, mostly from areas of the floodplain consumed by river bank erosion. It follows that rather little new knowledge is being brought to the area by inward migration.

Among those who were directly involved in agriculture, around 95% were subsistence farmers and 5% of farmers grow cash crops, while 95% of the respondents derived their income from agriculture and only 5% (schoolteacher and agriculture supervisor) depended on other forms of service. More than half the farmers interviewed said that they learned how to farm from previous generations, while less than 10% reported being taught modern methods by government agricultural extension workers.

Table 7.3 Variations of respondents' age and profession

Respondent Profession	Respondents age (years)					Total
	<= 30	31-40	41-50	51-60	>60	(%)
Farm own land	5	8	19	-	-	32
Employ people to farm land	-	1	5	3	-	9
Rent land out to farm	-	6	5	4	-	15
Cash crop farmer	-	4	1	-	-	5
Tenant farmer pays money for land	-	-	-	2	-	2
Tenant farmer pays crops for land	-	1	5	2	-	8
Perennial farm worker	4	2	-	1	-	7
Seasonal farm worker	4	3	-	-	-	7
School teacher	-	1	2	-	-	3
Chairman/members/village leaders	-	-	-	4	-	4
Local agricultural supervisor	-	-	-	2	-	2
Retired farmer (Due to age)	-	-	-	-	6	6
Total (%)	13	26	37	18	6	100

Table 7.4 Respondents' education levels

Level of Education	**Percentage**
Illiterate	38
Only sign name	19
Dropped at primary school	11
Secondary School Certificate	16
Higher Secondary Certificate	11
Undergraduate	4
Postgraduate	1

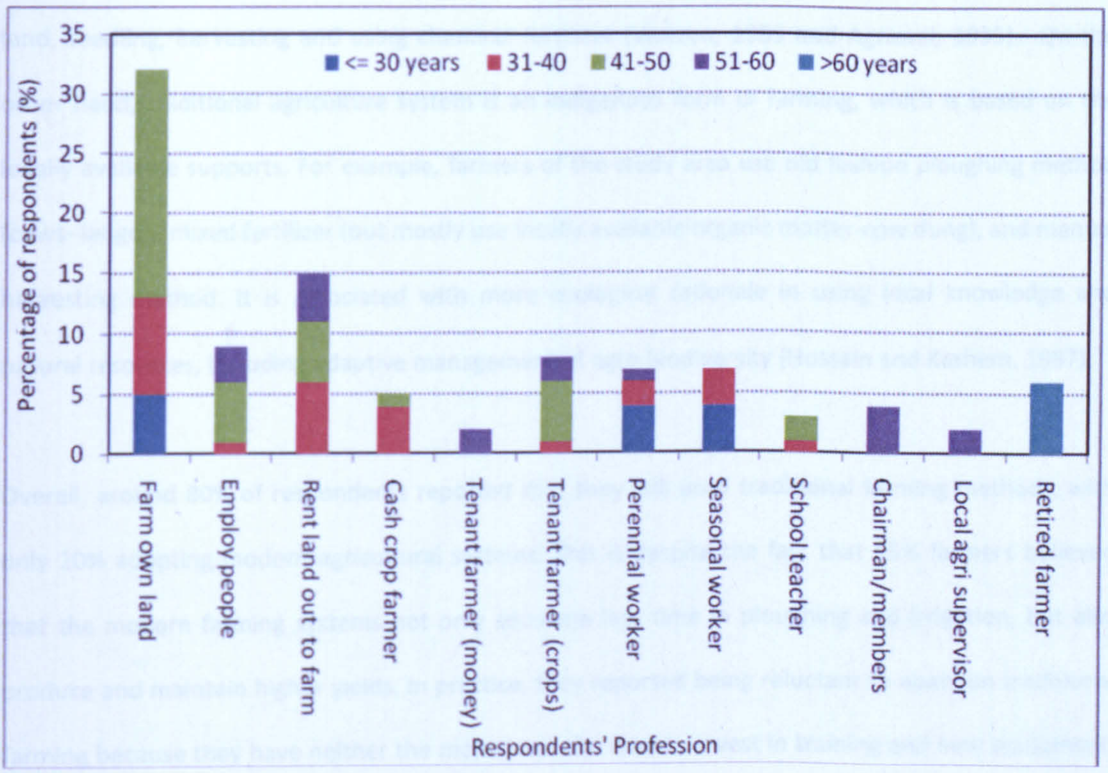


Figure 7.7 Variation of Respondents' professions and ages

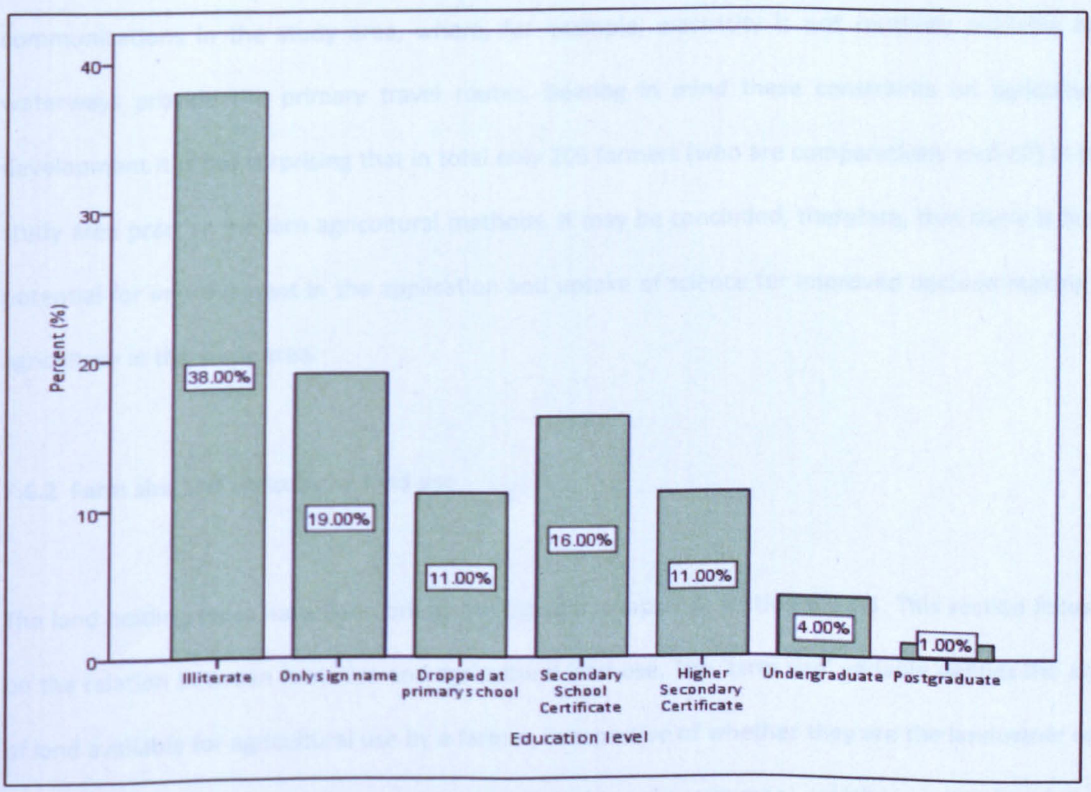


Figure 7.8 Variation in respondents' education levels

The modern agricultural system is centralized and associated with machinery facilities in ploughing land, seedling, harvesting and using chemical fertilizer (Warren, 1989 and Agrawal, 1995). On the other hand, traditional agriculture system is an indigenous form of farming, which is based on the locally available supports. For example, farmers of the study area use old fashion ploughing method (cows- langol), mixed fertilizer (but mostly use locally available organic matter-cow dung), and manual harvesting method. It is associated with more ecological rationale in using local knowledge and natural resources, including adaptive management of agro biodiversity (Hossain and Kashem, 1997).

Overall, around 80% of respondents reported that they still used traditional farming methods, with only 20% adopting modern agricultural systems. This is despite the fact that 65% farmers believed that the modern farming systems not only consume less time in ploughing and irrigation, but also produce and maintain higher yields. In practice, they reported being reluctant to abandon traditional farming because they have neither the money nor the time to invest in training and new equipment, and because they fear becoming dependent on help from the government as agricultural support has, in the past, proven unreliable. These behavioural factors are compounded by poor access to communications in the study area, where, for example, electricity is not routinely available and waterways provide the primary travel routes. Bearing in mind these constraints on agricultural development it is not surprising that in total only 205 farmers (who are comparatively well off) in the study area practise modern agricultural methods. It may be concluded, therefore, that there is huge potential for improvement in the application and uptake of science for improved decision making in agriculture in the study area.

7.6.2 Farm size and agricultural land use

The land holding types have been briefly described in chapter 6, section 6.3.1.1. This section focuses on the relation between farm size and agricultural land use. The 'farm size' variable defines the area of land available for agricultural use by a farmer, irrespective of whether they are the landowner or a tenant. Farm size was determined from the cadastral map (*mauza* map), which is used in Bangladesh to record plot ownership for tax revenue purpose (chapter 6, section 6.2.1.1 and Figure 6.1). The distribution of farm sizes in the study area is listed in Table 7.5 and illustrated in Figure 7.9. The total of 2330 plots has been classified into three groups; small farm (<1ha, 65%), medium farm (1-2ha, 29%) and large farm (6%) based on the available farm size.

There is also a link between farm size and land ownership. 85% of farmed by the owner themselves while 15% are cultivated by the tenants (Figure 7.10).

Table 7.5 Variation in percentage of farm size by farm owner

Farm ownership	Farm size (in hectares)			Total (%)
	Small (<1.0 ha)	Medium(1.0-2.0 ha)	Large (>2.0 ha)	
Owner	55.00	25.00	5.00	85.0
Tenant	10.00	4.00	1.00	15.0
Total (%)	65.00	29.00	6.00	100.00

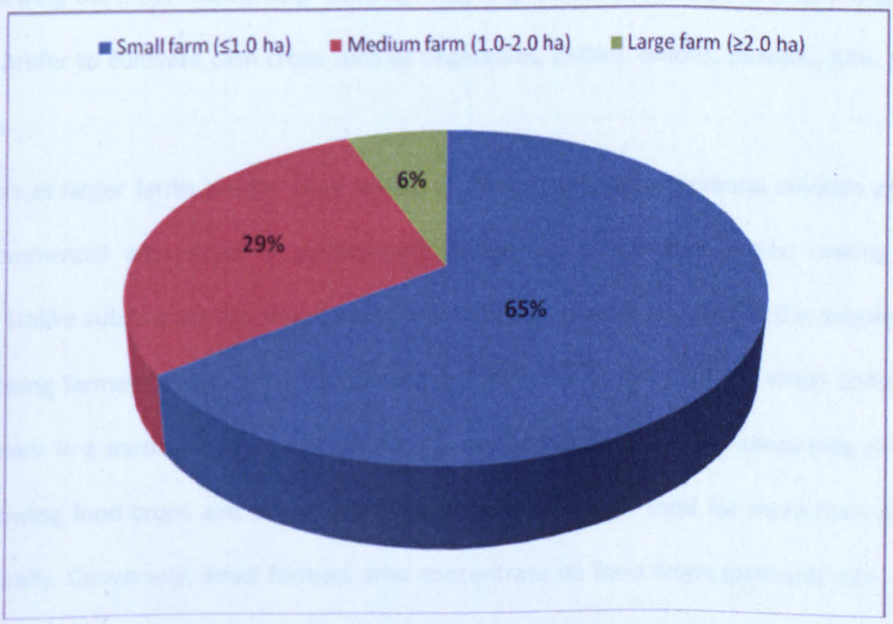


Figure 7.9 Variation in farm size

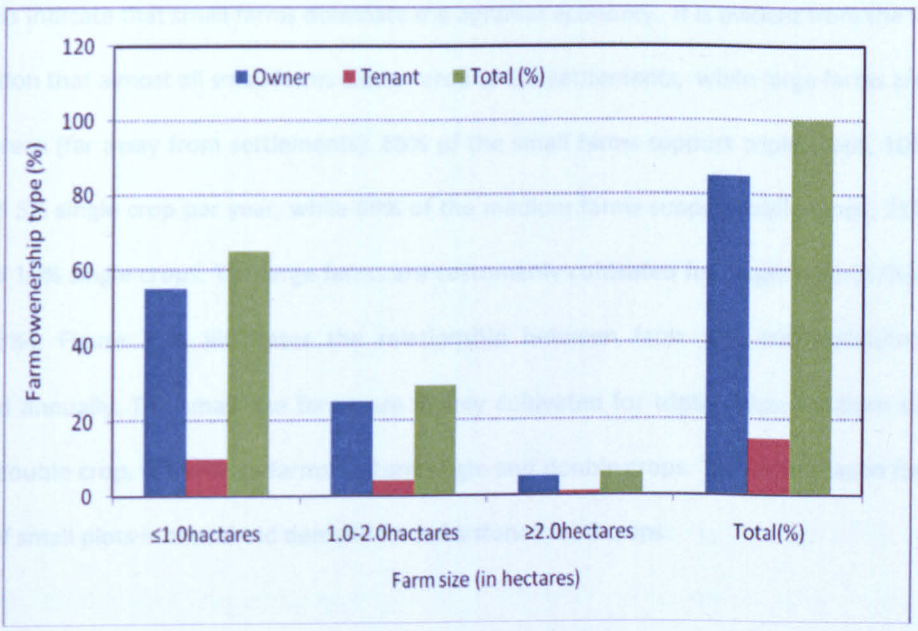


Figure 7.10 Variation of Farm size (land holding) by farm ownership

The tenant farmers pay the rent by crop sharing and/or cash depending on the tenancy agreement. It is evident that most small farms are cultivated by their owners, who subsist on the products of their labour and who make their own decisions on cropping. These farmers are particularly reluctant to rely on advice from government extension officers because they fear that this will not be forthcoming in time for sowing the crop. Conversely, those farming large plots do not depend on growing their own food and prefer to cultivate cash crops such as vegetables, chillies, onions, peanuts, jute, sugarcane, or sesame.

The owners of larger farms are far more willing to interact with governmental advisors and seek to gain a commercial advantage by participating in farming cooperatives when making land use decisions. Unlike subsistence farmers, commercial farmers (or more specifically the people who own the land being farmed) access available information on current market prices when deciding which crops to plant in a particular season. However, the growing season for cash crops may overlap with that for sowing food crops and this is why large farms are seldom used for more than one or two crops annually. Conversely, small farmers who concentrate on food crops (primarily rice, wheat, or lentils) can plant three crops per year as the growing and sowing seasons do not overlap. Hence, farm size influences decision making in terms of the basis upon which decisions are made and the options available for single, double or triple cropping (Table 7.6).

The results indicate that small farms dominate the agrarian economy. It is evident from the field level investigation that almost all small farms cluster around the settlements, while large farms are located in rural areas (far away from settlements). 85% of the small farms support triple crops, 10% double crops and 5% single crop per year, while 69% of the medium farms support triple crops, 21% double crops and 10% single crops. The large farms are customarily cultivated for single crop (67%) and two crops (33%). Figure 7.11 illustrates the relationship between farm size and agricultural crops supported annually. The small size farms are mainly cultivated for triple crops; medium size farms triple to double crop, while large farms feature single and double crops. The main reason for intense farming of small plots is household demand for subsistence food crops.

Table 7.6 Linkage between farm size and number of agricultural crops produced annually.

Farm size	Agricultural crops produce annually (%)			Total
	Single	Double	Triple	(%)
Small (<1ha)	3	7	55	65
Medium (1-2ha)	3	6	20	29
Large (>2ha)	4	2	-	6
Total (%)	10	15	75	100

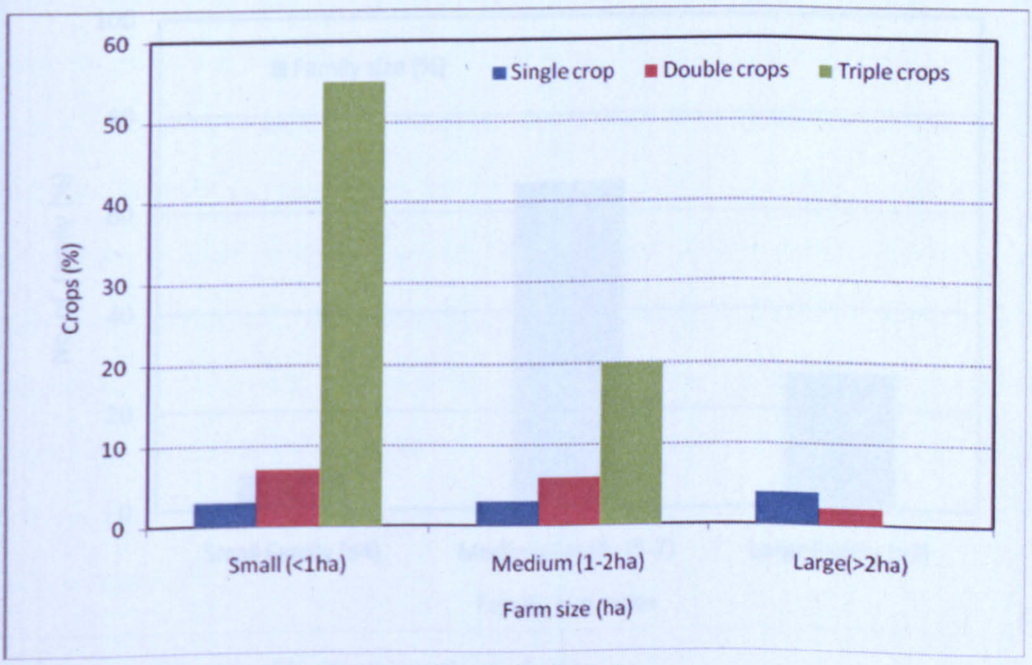


Figure 7.11 Agricultural land uses according to the farm size

7.6.3 Family size and agricultural crops selection

Agricultural land use decision making is influenced by family size. In Bangladesh, families are classed as small (≤ 4 persons), medium (5-7persons) and large (>7 persons). The results of investigations performed in this study indicate that the number of family members in agricultural households in the study area varied from two to ten (Figure 7.12). Medium sized families are dominant in the study area with two thirds of families falling into this size class. Just over a quarter of families are large, but small families are relatively rare, making up just 7% of the population.

Table 7.7 details the relationships between family size, agricultural employment and land use decisions that were revealed by the field survey. Practically everyone in medium (95%) and small (90%) sized families was engaged in agriculture. Employment was somewhat more diverse (80% in agriculture) in large families. However, in all cases the main income source was agriculture. Considering average annual incomes and expenditures, medium sized families had the highest deficit (-20%), followed by large families (-10%). Interestingly, only small families reported having an annual surplus (+10%). This probably reflects the fact that medium and large families have more dependents (old people or children) that rely on family members active in agricultural labouring to generate income. Conversely, medium and large families may have excess labour available, but due to the shortage of agricultural land in the area, they are often unable to gain income even as day labourers.

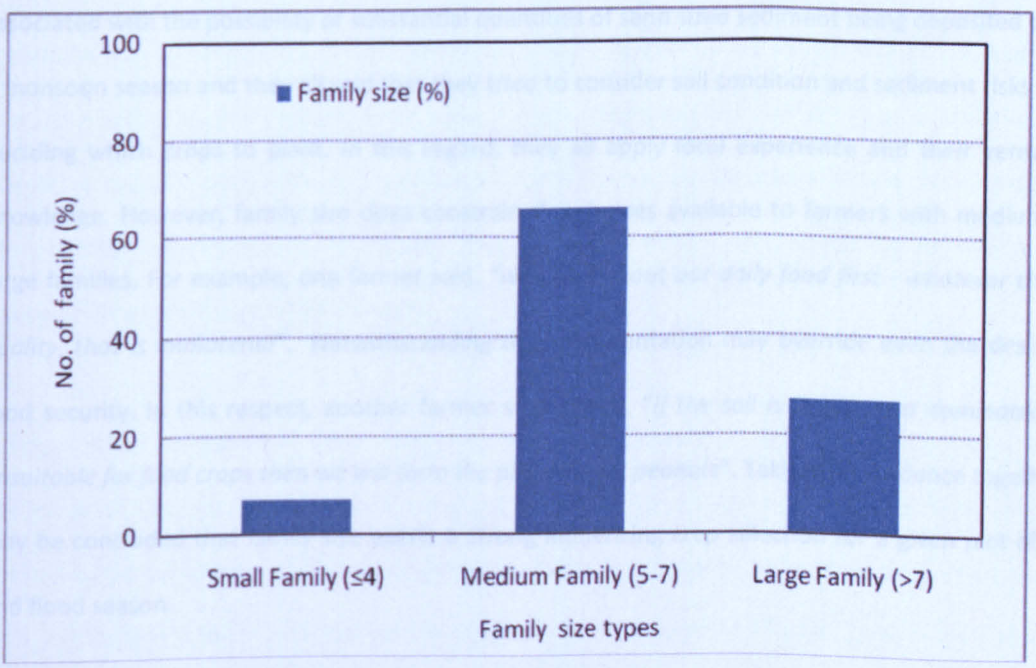


Figure 7.12 Distribution of family sizes in the study area

There is an inverse relationship between the family's size and the area of cultivable land per person available to them. This situation is exacerbated by population growth, which results in fragmentation of large farms when the land is divided between the heirs on the death of the patriarch or matriarch. In selecting crops for cultivation, medium and large families are primarily concerned about securing the family's food supply through intensively cultivating food crops.

Conversely, farmers with small families have relatively more land per person and so they can consider extending their land use to include cash crops. It is the option to grow cash crops that accounts for the average annual economic surplus enjoyed by small families. It is this surplus that allows small families to invest in modern agriculture systems, leading to higher yields especially of cash crops. Conversely, medium and some large families, who would like to modernise, are compelled by the need for food security to grow food crops that do not generate a cash surplus. They are locked into a cycle of intensive (three crop per year) farming that rules out the cash cropping needed to generate the excess income necessary to support investment in modern systems. Without governmental input and support, they will remain unable to adopt modern agricultural techniques.

The farmers surveyed were aware of the importance of soil quality and the risk to productivity associated with the possibility of substantial quantities of sand sized sediment being deposited during a monsoon season and they all said that they tried to consider soil condition and sediment risks when deciding which crops to plant. In this regard, they all apply local experience and their vernacular knowledge. However, family size does constrain the choices available to farmers with medium and large families. For example, one farmer said, *"we think about our daily food first - whatever the soil quality, that is immaterial"*. Notwithstanding this, sedimentation may override even the desire for food security. In this respect, another farmer stated that, *"if the soil is really sand dominated and unsuitable for food crops then we will farm the plot only for peanuts"*. Taking this evidence together, it may be concluded that family size exerts a strong influencing crop selection for a given plot of land and flood season.

7.6.4 Market price and agricultural crop selection

During the two major cropping seasons (*kharif* and *rabi*), the great majority of land in the study area (72%) is used for rice cultivation. Other popular crops are; oil seed (9%), wheat (5%), lentils (3%), jute (3%), peanuts (2%), vegetables (2%), and sugarcane, maize and chilli, all of which occupy about 1% of the area. Rice is the staple food in Bangladesh and so it is preferred regardless of market forces. However, selection of the secondary crops is influenced by fluctuations in their market prices. Table 7.8 summarises the results of the field survey of local market prices and farmers' crop selection preferences in 2007 and 2008.

The results show that market prices for four crops (including the main crops of rice, oil seeds and wheat, plus maize) rose in 2008 relative to 2007. In contrast, prices for lentils, jute, peanuts, vegetables, sugarcane and chillies all fell in 2008. According to the interviewees, farmers believe that prices vary not only due to over or under production resulting from natural flood variability, but also due to middle men who control the market and manipulate prices up or down for their own advantage.

According to the survey results in Table 7.9, farmers have different crop preferences depending on the volatility of the market price and their confidence in getting a good return on any cash crops they take to market. In this respect, they have a high preference for rice because it provides their household food security, while any surplus rice always fetches a good price at market. Preferences for other crops are related to farm size. This variation mainly occurs due to the contrasting socioeconomic conditions of the farmers.

Although small farmers have small plots, they have more flexibility to change crops according to the market price because they are not locked into subsistence agriculture using traditional methods. Medium sized farmers have fewer opportunities for selecting crops according to market price because they are focused primarily on securing the food supply for their households. Some large farms also have large families to support and are in a similar position. However, large farms that support small or medium sized families have more options because they have more land per person and so can respond to market prices more easily than those on the medium sized farms.

7.6.5 Farmers' vernacular knowledge and decision-making

Based on the results of the questionnaire, interview, group discussion and field observations reported in this chapter, sections 7.6.5.1 to 7.6.5.5, it is clear that farmers in the study area possess substantive knowledge concerning flood processes and the flood seasons, land types, soil qualities, sediment characteristics and moisture conditions in the study area. However, the degree to which they actually apply this knowledge in deciding which crops are most suitable for a given plot of land in a given season (as influenced by a particular flood), remains to be explored.

7.6.5.1 Farmers' knowledge of crop seasons

Although there are officially six seasons in Bangladesh; spring (*basanta*), summer (*grisma*), rainy (*Barsha*), autumn (*sarat*), late autumn (*hemonta*), winter (*shith*), as recognised by Brammer (1999), most farmers follow four seasons in planting and harvesting their crops (Table 7.9). In some areas, however, the post-monsoon and dry seasons are treated as a single season to produce; *Kharif-1* (Pre-monsoon), *Kharif-2* (monsoon) and *Rabi* (dry) cropping seasons. Hence, crop seasons vary somewhat from region to region, depending on local conventions (Brammer, 2002).

The results of the field survey establish that farmers in the study area follow the four-season pattern, although the planting and harvesting of some crops does not match the seasons exactly: that is, they are sown in one season but harvested in another (Paul, 1984; Ali, 2003; Rahman, 2005). The pre-monsoon season, which is known locally as *grismakal* and for which the associated crop season, is *prak-kharif*, runs from March to May. The weather is very hot and humid, with scattered rains starting late in March. Jute and *aus* (both local and HYV) paddy are the principal crops sown during this season.

Table 7.7 Influence of family size on employment, annual deficit/surplus and agricultural decision making in the study area (110 Taka = £1)

Family size	Employment (%)		Main income sources	Average income (Taka/Year)	Average expenditure (Taka/Year)	Deficit/surplus (± %)	Decision criteria on agricultural land use
	Agriculture	Non-agriculture					
Small (≤ 4)	90	10	▪ Agriculture	80,000	72,000	+ 10	▪ Intend to apply modern agricultural systems more Use the land for single, double or triple crops ▪ Emphasis on cash crops ▪ Combination of scientific and local knowledge
Medium (5-7)	95	5	▪ Agriculture	100,000	120,000	-20	▪ Use traditional agricultural systems ▪ Intensively farm the land using triple cropping ▪ Emphasis on food crops ▪ Based on mainly local knowledge
Large (>7)	80	20	▪ Agriculture ▪ Business	150,000	165,000	-10	▪ Practice both modern and traditional agricultural systems ▪ Intensively farm the land for triple crops ▪ Emphasis equally for food and cash crops ▪ Based on mainly local knowledge

Table 7.8 Local market prices for agricultural crops and farmers' crop selection preferences

Crops	Price (Taka/Mound)			Crop selection preference		
	2007	2008	Variation (± %)	SF	MF	LF
Rice	700-800	900-1,000	+33	+++	+++	+++
Oil seeds	800-1,000	1,200-1,300	+39	+++	++	+++
Wheat	1200-1400	1,000-1,100	+15	+	++	++
Lentils	1,500-1,600	1,300-1,500	-10	+	-	+
Jute	1,200-1,300	950-1,100	-18	-	-	-
Peanuts	600-700	500-600	-15	+	-	-
Vegetables	350-450	250-300	-31	++	++	-
Sugarcane	200-300	200-250	-10	-	-	-
Maize	800-1,000	1,200-1,300	+39	+++	++	+++
Green Chilli	500-600	300-400	-36	+	+	+

Sources: Key informants interviews and local market survey in 2007 and 2008

[**Note:** 110 Taka = £1 and 1 Mound = 40Kgs, SF = Small farmer (including landless and marginal farmers), MF = Medium farmer, LF = Large farmer; '+++' = high preference, '++' = moderate preference, '+' = low preference and '-' = very low preference].

Table 7.9 Farmers choices for agricultural crops based on Brammer's 1999 classification of the seasons

Seasons	Criterion	Name used by farmers	Local crop season	Principal crops sown
Pre-monsoon (March-May)	Hot-humid	*Grismakal*	*Prak-kharif*	Jute, rainfed *B. Aus* and *B.Aman* paddy
Monsoon (June-September)	Hot, humid, heavy rain	*Barshakal*	*Kharif/ Bhadai*	Transplanted, sown and HYV *Aman*
Post-monsoon (October-November)	Hot, humid, but less rain	*Hemantakal*	*Aghnai / Haimantic*	IRRI and *Boro* paddy, lentils and mustard
Dry season (December-February)	Dry, mild, sunny	*Shithkal*	*Rabi*	Oil seeds, wheat, peanuts, onion, sugarcane, winter vegetables

[**Note:** B. *Aus* = Broadcast *aus* paddy; *B. Aman*= Broadcast *aman* paddy; IRRI= A type of paddy invented by International Rice Research Institute, Philippines; Boro = Local variety paddy which grows in shallow water mainly during the dry season]

Farmers generally depend on the small amount of rain and rain-fed flooding when sowing these crops and prefer medium-high to medium-low land because these crops are vulnerable to deep inundation should monsoon floods arrive earlier than usual.

Farmers call the monsoon season *Brashakal* and the associated crop season is termed *Kharif/Bhadai.* This season is characterized by heavy rains and mixed rain-fed and river flooding that starts in June and persists until September. *Aman* (including broadcast, transplanted, high yield variety and deep water) paddy is the primary crop sown during this season.

It was observed in the field that most farmers who planted *aus* paddy during the pre-monsoon season actually sowed *aus* and *aman* seeds, mixed together. The a*us* paddy is harvested after 3-4 months – during the early monsoon season and before the peak of the monsoon flooding. This is important because *aus* paddy can only tolerate low depths of inundation. After the *aus* paddy has been harvested from land planted with mixed seeds, the *aman* paddy is allowed to continue growing, as it take 7-8 months for it to mature. As soon as the pre-monsoon season crop has been harvested from plots planted only with *aus* paddy, *aman* paddy plants are transplanted into those fields. *Aman* paddy grows well in either rain-fed or river floodwater and certain species of *aman* paddy (deep water *aman*) tolerate inundation depths up to 3m. Hence, farmers usually select this crop for medium-low to very-low land.

The jute planted during the pre-monsoon season is harvested during the peak of the monsoon flooding in July or early August. This is because abundant floodwater is required to process jute. After harvesting, most fields that have been used to grow jute are left currently fallow until the floodwaters have receded.

Farmers call the post-monsoon season *hemantakal* and the associated crop season *haimantic* or *aghani.* In most years, the weather is still hot and humid, though there is a lot less rainfall *aman* paddy is harvested and simultaneously a *boro* paddy crop is planted in low-lying areas of land that is still inundated, although it is recognised that flooding will recede completely by the end of November.

Lentils or mustard are sown in those areas of medium-low to very-low lying land that are no longer inundated, but which are still wet with floodwater.

The dry season is termed *shithkal* by farmers and the associated crop season is termed *rabi*. Oil seed, wheat, peanuts, onions, chillis, sugarcane, and different types of winter vegetables are planted in the fields in high and medium-high lands that were used to grow jute during the pre-monsoon and monsoon seasons, but which were left fallow during the post-monsoon season. These *rabi* crops are harvested at the end of February, with some of the land being immediately used for sesame or early *aus* paddy and jute.

This short account emphasises not only the intensity with which farmers practice agriculture year round, but also the close attention they must place on matching crops and seasonal practices to the type of land and anticipated flood behaviour. Consequently, the general scenario described here varies from season to season depending on short-term, local scale climatic fluctuations.

7.6.5.2 Farmers' knowledge of flooding

All the respondents referred to annual, monsoon flooding as being either *barsha* or *bonna* (Ralph, 1975; Islam, 1980; Paul, 1984). The great majority (85%) of respondents agreed that a (normal) *barsha* flood is one which: inundates crop lands (mostly *aman* paddy) to a depth of about 1m; does not flood village or homestead mounds, and; has a maximum duration of no more than about 2 months. However, some respondents (15%) believe that floodwaters up to 1.8m deep may still be considered *barsha* if agricultural crops are not damaged and daily life is not hampered. While the numerical threshold between *barsha* and *bonna* flooding was disputed by some respondents, they unanimously agreed that extreme flooding or *bonna* is a disastrous event that damages crops and properties while disrupting daily life.

Table 7.10 lists the flood damages recorded in 2007 and 2008. All respondents recognised that 2007 was an extreme flood (*bonna*), while 2008 was a normal flood or *barsha*, as there was no significant damage. In line with the finding of Brammer (2000), respondents generally expect *Barsha* events to occur most years, while a *bonna* is to be expected at 3 to 4 year intervals and a truly catastrophic flood is likely every 10 years or so.

Table 7.10 Comparison of flood damages recorded in 2007 and 2008 (Source: field survey)

Year	Damages	Flood type according to farmers	Respondents (%)
2007	▪ 15% *aus* paddy destroyed ▪ 40% *aman* paddy destroyed ▪ 100% of vegetable crop damaged ▪ 100% of fish washed away from khals, ditches and homestead ponds by flood water ▪ 75% of settlements inundated	*Bonna (*extreme flood*)*	100
2008	▪ 3% *Aus* paddy destroyed ▪ 8% *Aman* paddy destroyed ▪ 25% vegetable crop damaged ▪ No fish washed away ▪ No settlements inundated	*Barsha (*normal flood*)*	100

In terms of sediment deposition, the great majority (80%) of respondents understood that *bonna* floods carry more sediment than *barsha* events. Farmers characterised floodwater depth using vernacular measurements. For example, floodwater depth during *barsha* ranges form *huttopani or ekhatt* (up to knee height – just less than 50cm) to *komorpani/mazapani or dhuihaat* (up to the midriff – just over 90cm). They described *bonna* inundation as *bookpani* or *tinhaat* (greater than chest height – more than about 140cm). Farmers also used the term *dhaar* or *shroot* (running water) to differentiate *bonna* from *barsha* flooding, on the basis that floodwater that is perceptively flowing more widespread during *bonna* than *barsha.* They also note the colour and turbidity of the floodwater, inferring that sedimentation will be greater when and where it appears muddy and opaque. Practically all respondents (90%) appreciated the significance of sediment particle size (sand, silt, or clay) to soil quality, fertility, and agricultural productivity.

7.6.5.3 Farmers' knowledge of land types

Table 7.11 shows land types and soil classifications based on farmers' vernacular knowledge in comparison to official, scientifically based categories. The highest land type, making up just 8% of the study area, is termed *vite/dhanga/taan* (highland). It is defined as normally flood free and is used for settlements and homesteads. The associated soil comprises *Kada* and *poli maati*, which are clayey loam.

27% of the area is considered by farmers to be *chala/Kandi* (medium high land-1) that is inundated by normal floods to a depth of less than 30cm. Soils in this land type are *bele/bali/bailla* (sandy) soils suitable for early *rabi* season crops. 35% of land is *chwak* (medium high land-2) which is inundated by 30 to 90cm, and which features *poli maati* (silty) soil. This land is highly suitable for primary agricultural crops like *aus* and *aman* paddy, jute, sugarcane, lentils and mustard.

Farmers classed about 15% of the study area land as *naal* (medium low land) that is inundated to a depth of 90 to 180cm and has a *poli doas* (silty loam) soil suitable for broadcast and transplanted *aus* and *aman* paddy or jute. The fifth level of land is *khal* and *byde* (low land) that comprises 7% of the area and which is annually inundated to a depth between 180 and 300cm. The *antel/kada and Poli maati* (Silty, clayey) soils in fifth level land are suitable only for dry season, *rabi crops*. Farmers' class about 5% of the study area as *beel* (very low land) that floods to a depth greater than 300cm and which remain inundated for more than 9 months. The *antel/kada maati* (clayey soil) here is suitable for *boro* paddy. The lowest 3% of land in the study area is *nodi* (river land) that is perennially flooded to a depth greater than 300cm and which features *bali, poli, kada* and *pani* (sand, silt, clay and water). Parts of this area near the riverbank sides may emerge during the dry season, at which time it may be used for seedbeds.

The results of the field survey demonstrate that the VK on land type listed in Table 6.11 is widely used when deciding what crop to plant on a plot of land. However, farmers do not always rely on the generalised links between land types and soils listed there. They also consider soil type and crop suitability more specifically, factoring in their understanding of the role of flood-driven sedimentation, based on VK and their personal experience.

7.6.5.4 Farmers' knowledge of soil types and crop suitability

The question of how farmers identify the type of soil on a given plot of land and rate its suitability for a particular crop was investigated in the field survey. The results reveal that farmers use a substantial body of vernacular knowledge in identifying the soil characteristics, most of which is qualitative rather than quantitative.

For example, it has been reported by Ali (2003) that farmers seek to discern soil suitability based on characteristics such as; texture, structure, bulk density, porosity or drainage, moisture content and the presence or absence of organic matter .

In the surveyed group, three quarters of farmers said they use only indigenous methods when assessing the soil including, visual observation of soil colour (Photograph 7.1), noting the abundance of weeds (Photograph 7.2), estimating the wetness (Photograph 7.3), rubbing the soil between their fingers, observing the surface lumpiness during tilling (Photograph 7.4), observing cracks (Photograph 7.5), throwing water onto the soil and tasting it with their tongue (Table 7.12).

When farmers refer to the soil and sediment properties of a plot, their descriptions are complicated by inconsistencies in terminology. In Bengali, the word, *'maati'* refers to soil and *'polol' or 'poli'* means sediment. However, about a third of local farmers used the term *'polol'* to indicate either soil or sediment, while two thirds of them used *'polol' or 'poli'* specifically to indicate fine-grained, flood-borne particles usually carried by normal (*barsha*) flood events and excluding the coarser sandy particles (*bele*) deposited by *bonna* flooding. These farmers add the suffix *'maati'* after each category of particles to describe a soil type such as, *'bele maati'* - which denotes a 'sandy soil'.

Table 7.11 Farmers' typology for land types and soils in the study area around *Bara Banna* village

General land type	Flood depth (cm)	Farmers' classification	Farmers' inundation perception	Farmers' soil typology	Soil texture	% of unit	Common agricultural use
High land (HL)	0	*Vita, Dhaanga, taan*	Normally above flood level but flooded only with catastrophic flood	*Kada+poli maati*	Clay loam	8	Settlement, Homestead vegetation
Medium high Land (MHL-1)	≤30	*Chala, Kandi*	Crops inundated but not damaged	*Bali/Bailla/Bele mati*	Sand	27	Early *rabi* crops
Medium high land(MHL-2)	30-90	*Chwak*	Crops inundated and partially damaged	*Poli maati*	Silt loam	35	B. *Aus* & T, *Aman*, paddy, Jute
Medium low land (ML)	90-180	*Naal*	Crops inundated and mostly damaged	*Poli doas maati*	Silty clay loam	15	*Aus*+ B. *Aman*, Jute
Low land (LL)	180-300	*Khal, Byde*	Only dry season's crops available	*Antel/ kada +Poli maati*	Silt clay	7	Irri and Local *boro* paddy
Very low land (VLL)	≥ 300 flooded > 9 months	*Beel*	Only dry season's crops available	*Antel /kada maati*	clay	5	Local *boro*, Deep water *Aman* paddy
Bottom land (BL)	Mainly≥300cm, Perennially wet	*Nodi*	Year round inundation	*Bali, poli , kada and pani*	Sand, clay and water	3	Mainly Water ways

Note: The general land type and flooding classification was developed on the country's reconnaissance soil surveys and in the agro ecological zones (AEZ) studies (FAO, 1988). The Master Plan Organization (MPO, 1987) adopted the system with some modifications considering the local variability.

B. *Aus*= Broadcast aus paddy, *Rabi* crops= Dry season crops, T. *Aman*= Transplanted *aman, maati*= native name of soil and all itlaci name represents the local and native names.

When categorizing the soil, farmers commonly use a term *'bunot'*, which refers to soil texture (Ali, 2003; Payton *et al.*, 2003). However, practically all the farmers interviewed (90%) assess *bonot* (texture) based on soil colour. A whitish colour is interpreted as *bele maati* (sandy soil), grey colour soil is *poli maati* (silty soil), and dark grey colour soil is *aintel maati* (clay soil).

Two thirds of farmers further classify the soil into a sub-group based on the abundance of weeds that spring up on fallow ground. Highly dense weeds is taken to indicate *poli doas maati* (silt loam soil), moderately dense weeds indicate *bele doas maati* (sandy loam soil) while low-density weeds indicate *bele maati* (sandy soil).

Three quarters of the farmers interviewed assess soil structure based on an examination of its consistency, which is usually performed by rubbing the soil between their fingers. A dry consistency with loosen compactness indicates *bele maati* (sandy soil), a friable consistency with medium compactness is *poli maati* (silt soil) and a sticky consistency with high compactness is *aintel maati* (clay soil).

Four fifths of farmers estimate bulk density through tilling. Large or medium-sized lumps result from the high aggregation of particles suggesting that the soil is *aintel maati* (clay soil). Small to very small lumps resulting from moderate aggregation suggest *poli maati* (silt soil), while a complete absence of lumps due to very low aggregation indicates *bele maati* (sandy soil).

Two thirds of farmers reported examining land drainage with the purpose of checking whether the soil will be able to retain irrigation water for use by crops (especially paddy) or whether it will be lost through infiltration. This involves throwing water on to the soil and observing how quickly it seeps away. They do this repeatedly and judge soil drainage condition and crop suitability after 2 or 3 times, when the soil seems completely wet. A high infiltration rate indicates the presence of coarse particles and so the soil is inferred to be *bele maati* (sandy soil), while medium and low infiltration rates indicate *poli maati* (silt soil) and *aintel maati* (clay soil), respectively.

Three quarters of farmers estimate moisture content based on how a handful of soil feels in their hand coupled with visual observation of wetness. A soil that feels light holds little moisture and is taken to be *bele maati* (sandy soil). Medium weight soils with moderate moisture are assumed to be *poli maati* (silt soil) and heavy soils with high moisture are *aintel maati* (clay soil). However, farmers also factor in a consideration of the abundance of weeds and soil colour when assessing soil moisture content.

All the respondents were aware to a greater or lesser degree of the importance of soil acidity *(amlota)* or alkalinity (*Khaarokiota*), which they also related to soil colour. In practice, a whitish colour is taken to indicate low acidity/high alkalinity, a grey colour indicates moderate acidity and alkalinity, and a dark grey colour indicates high acidity/low alkalinity. A further test for acidity was mentioned by 68% of respondents, who said that they taste the soil, using their tongue to assess its acidity. They use the term *'khar'* describe the irritating taste of high acidity. Soil with a strong *khar* is classed as *aintel maati* (clay soil), while *poli maati* (silty soil) has a slightly irritating taste and the moderately low acidity *bele maati* (sandy soil) is very much less irritating to the taste buds. The farmers reported working together as a network in establishing the presence or absence of organic matter in their soils.

Many farmers simply rely on the density of weeds to indicate organic matter content. However, a few of the farmers with longer-term experience, use a reciprocal relationship they have discovered between the level of organic matter in the form of decomposed cow dung manure; the presence of live earthworms in the soil, and whether rice stock or any vegetative material has been added to the soil.

The vernacular knowledge concerning soil types and attributes possessed by the farmers was compared with the scientific guidance provided by the SRDI (Soil Research Development Institute, Bangladesh) which is based on the both physical and chemical properties of soil at *upazila* level (third lowest administrative unit) and found a variation ranges ± 3 to ±15% (Table 7.12).

Considering all of the indicators together, farmers in the study area around *Bara Bannia* village classify the soil into three broad types and six sub-types. Table 7.13 presents summary results on local soil typology, approximate grain size distribution, location, percentage of the total area and rating in terms of crop suitability.

The soil classes used by farmers are; *bele maati* (sandy soil), *bele doas maati* (sandy loam soil), *poli maati* (silt soil) *poli doas maati* (silt loam soil) and *aintel maati* (clay soil) and *aintel doas maati* (clay loam soil).

Most of the 10% of the study area featuring *bele maati* (sandy soil) is found on the natural levees (*nodir teer)* near the main river and its distributary channels. Farmers characterise the particle size distribution of this soil as sand - 70%, silt - 25% and clay - 5%. Laboratory PSA performed in this study found the average size distribution to be sand - 77%, silt - 14%, and clay - 9%. The farmers' VK and the science-based values are therefore within ± 7% of each other. The majority (65%) of respondents classed this soil as as *motamoti* (medium) in terms of quality and ranked it fourth in terms of suitability for growing crops *aus* paddy, peanuts, potatoes, and sesame were named as the preferred crops for *bele maati.*

Bele doas maati (sandy loam soil) makes up 15% of the study area and is found in *danga or kandi* areas adjacent to the natural levee and extending into the back slope. Farmers characterised this soil as containing; sand - 60%, silt - 30% and clay - 10%. The equivalent figures from laboratory PSA were 72%, 20%, and 8%, indicating agreement to ± 8%. There was agreement amongst 70% of farmers that the quality of this soil is good (*bhalo*), ranking it third in suitability for cropping. This soil is particularly suitable for broadcast or transplanted *aus* and *aman* paddy (including local and high yield varieties (HYV), jute, oil seeds, wheat, and lentils. *Poli maati* (silty soil) is across 25% of the study area in the upper back slope (*naal jomi*). Farmers characterise it as; sand - 30%, silt - 60% and clay - 10%. The equivalent figures from laboratory analysis are; 18%, 77% and 15%: an average variation of ± 11%. 68% of respondents classed this soil as better (*beshi bhalo*) in terms of quality, ranking it second in

Table 7.12 Farmers' techniques for assessing soil type and comparison to SRDI (Soil Research Development Institute) report to assess the accuracy level

Physical properties of soil	Framers' determination techniques		Criteria	Soil Classification by farmers	English name	Percentage of total farmers	Accuracy level to SRDI Soil Class (± %)
Texture	Visual perception	colour	Whitish colour	*Bele maati*	Sandy soil	90	8-10
			Grey colour	*Poli maati*	Silt soil		
			Dark grey colour	*Aintel maati*	Clay soil		
		Abundance of vegetation	High density	*Poli-Doas maati*	Silt loam soil	63	10-15
			Moderate density	*Bele- Doas*	Sandy loam soil		
			Low density	*Bele*	Sandy soil		
Structure	Rub soil between fingers	Dry	Loose compactness	*Bele maati*	Sandy soil	75	7-9
		Friable	Medium compactness	*Poli maati*	Silt soil		
		Sticky	High compactness	*Aintel maati*	Clay soil		
Bulk density	Tilling	High or Medium lumps	High aggregation	*Aintel maati*	Clay soil	80	3-6
		Small-very small lumps	Moderate aggregation	*Poli maati*	Silt soil		
		No lumps	Less aggregation	*Bele maati*	Sandy soil		
Drainage	Throw water on the soil	High infiltration	Well drained	*Bele maati*	Sandy soil	65	5-7
		Medium infiltration	Medium drainage	*Poli maati*	Silt soil		
		Low infiltration	Poor drainage	*Aintel maati*	Clay soil		
Moisture	Feel the handful soil weight and wetness	Light	Low moisture	*Bele maati*	Sandy soil	75	6-10
		Medium	Optimum moisture	*Poli maati*	Silt soil		
		Heavy	High moisture	*Aintel maati*	Clay soil		
Acidity	Taste with tongue	Irritating	High acidity	*Aintel maati*	Clay soil	68	10-12
		low irritating	Moderate-low acidity	*Poli maati*	Silt soil		
		Very low irritating	Very low acidity	*Bele maati*	Sandy soil		

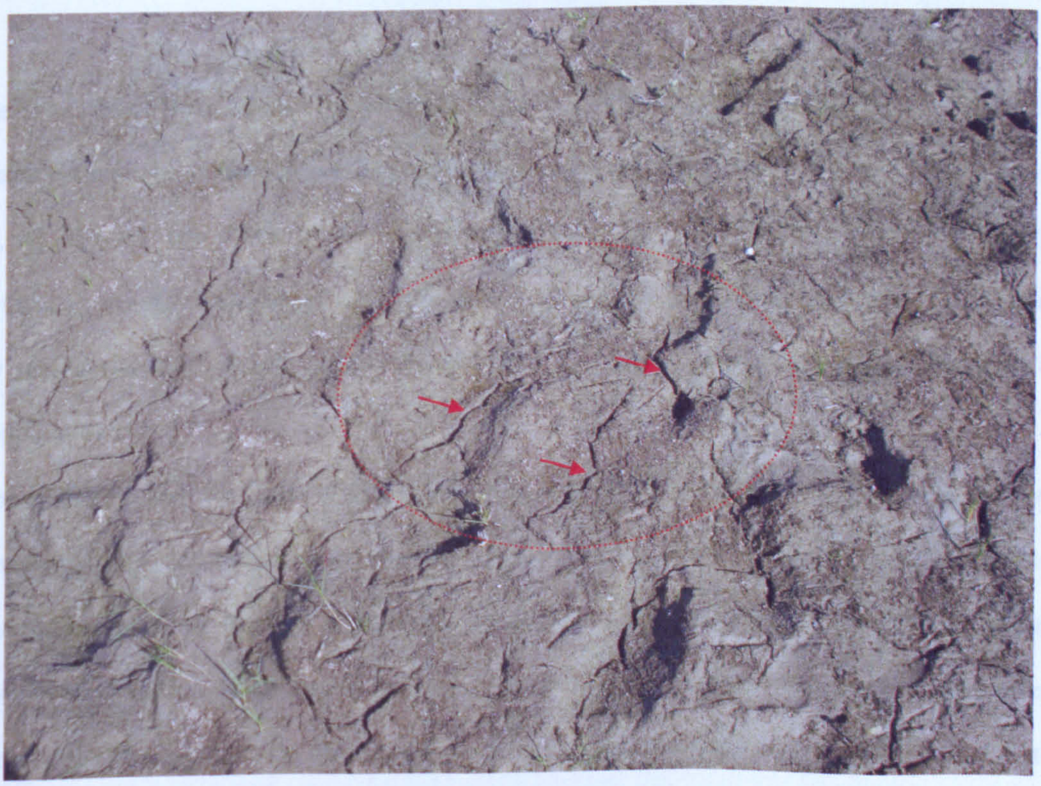
(a) (b) (c)

Photograph 7.1 (a) Whitish colour suggests a sand dominated soil, (b) grey colour suggests a silt dominated soil or (c) dark grey colour suggests a clay dominated soil

Photograph 7.2 Farmers assess soil type based on the abundance of weeds

Photograph 7.3 Farmers assess soil moisture and quality based on wetness

Photograph 7.4 Farmers observe surface lumpiness during tilling to assess sand, silt, and clay content



Photograph 7.5 Farmers take cracking to indicate a low sand content

terms of suitability. Preferred crops include broadcast or transplanted *aus* and *aman* paddy (local and HYV), jute, sugarcane, oil seeds, wheat and lentils.

Poli doas maati (silt loam soil) is the most commonly encountered soil, covering 45% of the study area in the lower back slope (*naal and chwak*). In terms of VK it is thought to contain; sand - 20%, silt - 65% and clay - 15%. This compares to 12%, 80%, and 8% according to laboratory analysis: an average variation of ±10%. Four fifths of farmers described this as best (*sobcheye bhalo*) in terms of quality and ranked it first in terms of suitability. This soil is highly suitable for any crop with the exception of peanuts.

Aintel maati (clay soil) is found in the lower back swamps *(beels)* that comprise a quarter of the study area. It is believed to comprise; sand - 5%, silt - 30% and clay - 65%, compared to 6%, 25%, and 69% according to laboratory analysis; an average variation of ±3%. Most (60%) farmers believe this soil to be of very poor quality (*khub mondho maati)* and they ranked it last (sixth) in terms of suitability for cropping. Only *boro* paddy, mustard, and lentils can be grown in *aintel maati.*

Aintel doas maati (clay silt soil) is found in the upper back swamp areas (*beels*) and along the floodplain channels (*khals*) that make up just 3% of the study area. It is thought to comprise; sand - 15%, silt -25% and clay - 60%. The equivalent figures based on scientific measurement are; 8%, 30% and 62%: an average variation of ± 5%. The quality of *aintel doas maati* is better than *aintel maati* (clay soil) but is still marginal to poor (*mondo maati*). Farmers ranked the soil fifth in terms of cropping suitability.

As described in the methods of data collection section, information related to the farmers' assessment of the soil texture was collected through both formal and informal discussion and in-depth interviews with the key informants. Most of the farmers provided information on the percentages of sand, silt and clay in different soils in a qualitative form. For example, *bele maati* (sandy soil) was described by the farmers as whitish colour, lacking in compactness, dry, little aggregation without lumpiness, very high infiltration rate, low moisture content, less vegetation cover and very low level of irritation on the tongue (indicating neutral acidity/alkalinity).

Table 7.13 Farmers' soil typology, location, quality and crop suitability based on vernacular knowledge and qualitative assessment.

Soil classification by farmers		Land level relative to river bank	Estimated and actual grain size distributions (%)			Farmers rating of soil quality	Crop suitability	Respondents (%)	Occupied area (%)
Soil type	Soil sub-type		Sand	Silt	Clay				
Bele maati (Sandy soil)	*Bele maati* (Sandy soil)	*Nodir teer* (Natural levee)	70 (77)	25 (14)	5 (9)	*Motamoti* (Medium) [4]	Peanuts, potato, Sesame, *Aus* paddy	65	10
	Bele-doas maati (sandy loam soil)	*Danga/Kandi/taan* (Adjacent to levee)	60 (72)	30 (20)	10 (8)	*Bhalo* (Good) [3]	*Aus* & *Aman* paddy, Jute, oil seeds, wheat, lentil	70	15
Poli maati (Silt soil)	*Poli maati* (Silt soil)	*Naal* (Upper back slope)	30 (18)	60 (77)	10 (15)	*Beshi Bhalo* (Better) [2]	*Aus* & *Aman* paddy, jute, sugarcane, wheat, Sesame, lentils	68	25
	Poli doas maati (Silt loam soil)	*Naal /chwak* (Lower Back slope)	20 (12)	65 (80)	15 (8)	*Sobcheye Bhalo* (Best) [1]	*Aus* & *Aman* paddy, jute, sugarcane, wheat, Oil-seeds, legumes, sesame, lentils, IRRI Paddy	80	45
Aintel maati (Clay soil)	*Aintel maati* (Clay soil)	*Beel* (Lower Back swamp)	5 (6)	30 (25)	65 (69)	*Khub mondho* (Very poor) [6]	*Boro* paddy, lentils, mustard	60	2
	Aintel doas maati (Clay loam soil)	*Beel* (Upper back swamp) & *Khal* (back slope)	15 (8)	25 (30)	60 (62)	*Mondho* (Marginal to Poor) [5]	HYV *aman*, *boro* paddy, lentils,	50	3

[**Note:** Estimated size distribution is based on farmers' opinions; results of laboratory analysis are given in brackets; and Figure following description of soil quality in brackets indicates the soil quality ranking from 1 (best) to 6 (very poor)]

Literate farmers additionally offered estimates of the size characteristics of differently named soils. For example, they described *bele maati* (sandy soil) as consisting of approximately 70% sand, 25% silt and 5% clay particles. These semi-quantitative definitions of the named soils provided the basis for direct comparison with the particle size distributions obtained in this study through laser diffraction, to assess the accuracy and reliability of the farmers' vernacular knowledge concerning soil properties (Table 7.13). In making this comparison, it should be borne in mind that neither vernacular or scientific knowledge is 'correct'. Certainly, the percentages of sand, silt and clay in the estimated size distributions in table 7.13 would be different if other farmers' had been consulted. However, the 'actual' size distributions would also be different has PSA been based on a technique other than laser diffraction. The fact is that the farmers questioned were a representative sample of key stakeholders in the study area – validating the estimated grain size distributions. Similarly, laser diffraction is well suited to PSA of fine sediments (<63μm). Hence, it is reasonable to compare the particle size distributions based on farmers' assessments with those based on scientific analysis while bearing in mind that, in both cases, different techniques would have produced different size distributions (Table. 7.13)

This investigation of the ways farmers test, characterise and classify soils to develop VK on soil quality and suitability for cropping has established that they possess a deep and intimate understanding of soil and crop associations, which they apply when deciding which agricultural crops to plant in a particular plot of land. Reasonable agreement between the particle size distributions estimated by farmers and measured scientifically to a degree validates the farmers' vernacular assessment of soil properties more generally.

7.6.5.5 Farmers' responses to uncertainty concerning flood and sediment dynamics

As established in Section 7.6.5.2, farmers not only recognise the significance of monsoon flooding to floodplain agriculture, but also understand that the timing, magnitude, and duration of flooding vary from year to year in ways that are largely unpredictable. Uncertainty concerning flood dynamics is then a key factor in crop selection, especially as the characteristics of flood-borne sediments vary with flood type and these characteristics impact on the quality of the soil and its suitability for cropping. Most farmers interviewed modify their agricultural practices in ways designed to reduce the risks associated with uncertainty concerning flood dynamics and they make non-structural adjustments intended to protect their crops actually during the flood. Many of these measures centre on encouraging the deposition of fine sediment within agricultural crops (especially, *aman* paddy and sugarcane) that naturally trap sediments anyway (Table 7.14).

Rashid and Paul (1989) noted that Bangladeshi farmers have carefully selected crops to be planted during the pre-monsoon season for centuries, and Haque and Zaman (1993) showed that farmers' indigenous knowledge of agricultural adjustments to flood hazards has over decades made an enormous contribution to crop productivity and the management of sedimentation on the floodplains of Bangladesh. It is evident from the results of questionnaires and interviews conducted in the village at the centre of the study area that contemporary farmers continue the practices developed during the previous decades and centuries. Today's farmers expect a flood every summer but are aware that it may be normal, abnormal, or catastrophic. Most believe that an abnormal flood will occur at 4 to 5 yearly intervals and they expect a catastrophic flood about once a decade, based on long experience. For example, prior to the 2007 flood, the previous catastrophic event happened in 1998. Consequently, farmers were aware that an abnormal or catastrophic flood was due and they factored this into their crop selection, favouring crops that could tolerate abnormally high water levels. However, they also recognised that there was no certainty that an abnormal event would occur and so they considered this eventuality too.

For example, during the pre-monsoon seasons in both 2007 and 2008, farmers planted *taan jomi* (natural levee) and *naal jomi* (back slope) land with *both* broadcast *aus and aman* paddy in the same plot of land. This represents a form of adaptation to the possible occurrence of abnormal flooding. *Aus* paddy is highly productive but can only tolerate shallow flooding. It matures in mid-July and must be harvested by the end of August at the latest. If flooding starts earlier than usual, is deeper than expected or persists into September, the entire *aus* crop may be lost. Conversely, *aman* paddy is less productive but it can tolerate deep floodwater and is harvested after the floodwater recedes. Farmers have also learned that this type of Inter-cultivation of mixed *aus* and *aman* paddy is also effective in slowing flood flow velocities and filtering suspended sediment, resulting in even deposition of fine sediment over the plot. Thus, farmers use their VK in deciding when to plant two *kharif* (monsoon) crops during the pre-flood season. This approach to managing uncertainty and selecting crops to affect flood processes is widely practiced not only in the study area but also throughout the Jamuna-Brahmaputra floodplain (Paul, 1984).

Another indigenous technique observed during the 2007 flood, was strategic placing of bamboo fencing by around a quarter of farmers, with the intention of protecting crops from invasion by water hyacinth. This simultaneously controlled floodwater flow velocity and triggered deposition of coarse sediment in front of the fencing. In 2008, 40% of farmers interviewed additionally cultivated *dhonchey (sesbania)* (Photograph 7.6) on plots that could not be used for food or cash crops due to sand deposited by the 2007 event. This is a multipurpose crop (its seeds are used for cattle feed, and the stems are used as fuel), which protects the land from water hyacinth, reduces floodwater velocities and traps fine sediment to accelerate the recovery of soil fertility following damage by sand deposition.

Very low land in the study area (*dopa jomi/beel*) is classed in traditional VK as unsuitable for cropping. However, the drive to increase food production to keep pace with demand from a growing population has led to an indigenous cropping adjustment in which low areas of the beds of back swamp beels, channel beds, and shallow ox bow lakes are cultivated for local variety, deep water (*Chamara /vasha aman)* paddy (Photograph 7.7). This is an especially flood tolerant paddy for which stem lengths can exceed 200cm and which can grow 10 to 15cm per day, to keep pace with the rising of floodwater during an abnormal event. In 2007 and 2008, 10% and 12% of respondents planted *Chamara/vasha aman* paddy in low-lying areas, demonstrating the willingness of farmers to take advantage of new and innovative opportunities for crop selection.

Following flood water recession, farmers re-evaluate soil quality and crop suitability depending on the amount and calibre of fresh sediment deposited on the land, ranging from *bele* (sand) to *aintel* (clay)

Photograph 7.6 *Dhonchey (sesbania)* is a multipurpose, flood tolerant crop used for flow and sediment management

Photograph 7.7 Local variety *chamara/vhasa aman* (deep-water rice) selected to improve the productivity of very low land and guard against rapid, deep flooding as it can grow at a rate that keeps pace with the rising flood waters.

Table 7.14 Farmers adjustments and responses to uncertainty and decision making on seasonal crop selection

Flood types	Land level	Adjustments		Sediment typology by farmers after flood	Farmers' decision on land use	
		Pre-flood	During flood		*Rabi* crops	*Kharif* crops
		Crop selection	Non-structural measures			
Bonna (abnormal flood, 2007)	*Taan jomi* (*Natural levee*)	Inter-cultivation of broadcast *aus-aman* paddy, jute and sugarcane	▪ Placing bamboo fencing to protect the *aman* paddy from water hyacinth (20)	▪ *Bele maati* (sandy soil) ▪ *Bele doas maati* (sandy loam soil)	▪ Peanuts ▪ Lentils, potato	▪ *Sesbania* ▪ *Aus* paddy, jute
	Naal jomi (Back slope)	Intercultural cultivation of broadcast *aus-aman* paddy, jute	▪ Placing bamboo fencing to protect the *aman* paddy from water hyacinth (8)	▪ *Poli maati* (silt soil) ▪ *Poli doas maati* (silt loam soil)	▪ Lentils, mustard, onion, maze, wheat ▪ Lentils, mustard, onion, maze, wheat & legumes	▪ *Aus* and *aman* paddy, jute ▪ *Aus* and *aman* paddy, jute
	Dopa jomi /Beel (Back swamps, scours, shallow bed of ox bow lake)	*Chamara/vasha aman* paddy	▪ Naturally adjusted to flood water level through steam growth (10)	▪ *Aintel doas maati* (clay loam soil) ▪ *Aintel maati* (clay soil)	▪ Lentils and mustard ▪ Mustard, *Boro* paddy	▪ Deep water *Aman* paddy ▪ Deep water *Aman* paddy
Barsha (*Normal* flood, 2008)	*Taan jomi* (*Natural levee*)	Cultivated *Dhonchey* (*sesbania*) and broadcast *Aman* paddy	▪ Placing bamboo fencing and retaining *dhonchey* (*sesbania*) along the edge of the land to protect the *aman* paddy from water hyacinth, water flow and coarse sediment (15)	▪ *Bele doas maati* (sandy loam soil)	▪ Lentils, potato, onion	▪ *Aus* and *aman* paddy, jute
	Naal jomi (Back slope)	Inter-cultivation of broadcast *aus-aman* paddy, Jute	▪ Keeping *dhonchey* (*sesbania*) along the edge of the land to protect the *aman* paddy from water hyacinth, water flow and coarse sediment (25)	▪ *Poli doas maati* (silt loam soil)	▪ Lentils, mustard, onion, maze, wheat & legumes	▪ *Aus* and *aman* paddy, jute, sugarcane
	Dopa jomi /Beel (Back swamps, scours, shallow beds of ox bow lakes)	*Chamara /vasha aman* paddy	▪ Naturally adjusted to the flood water level through rapid stem growth (12)	▪ *Aintel doas maati* (clay loam soil)	▪ Lentils and mustard, *boro* paddy	▪ Deep water *Aman* paddy

[**Note:** Figures in parenthesis indicate the percentage of farmers using this measure] in relation to land level flood type *bonna* or *barsha* (Table 7.14). Where it is found that sand deposition has reduced soil quality to the point that it is unsuited to paddy, peanuts are planted as a *rabi* (dry season) crop. After harvesting the peanuts, *dhonchey* (*sesbania*) is planted to help fertility recover in time for the planting of food or cash crops in the following season. This example demonstrates how farmers respond to sand deposition by selecting crops that are not only suited to the currently reduced soil quality, but which are specifically selected to restore soil quality and reinstate the desired crop cycle in the shortest possible time. This further stresses how farmers in the study village apply their vernacular knowledge actively as well as passively when selecting their crops.

7.7 Physical model in the Bayesian Network Decision Support System (BNDSS)

The model within the BNDSS that accounts for sediment deposition thickness and calibre (sand, silt or clay) is shown in Figure 7.13. In the sediment model, landform (natural levee, back slope and back swamp) is considered to be the independent variable, which affects the dependent variables flood depth, flood duration, flood flow velocity and vegetation density/abundance. The results of the field investigation (Table 7.15) suggest that flood depth and duration, flow velocity and vegetation density do indeed vary according to landform.

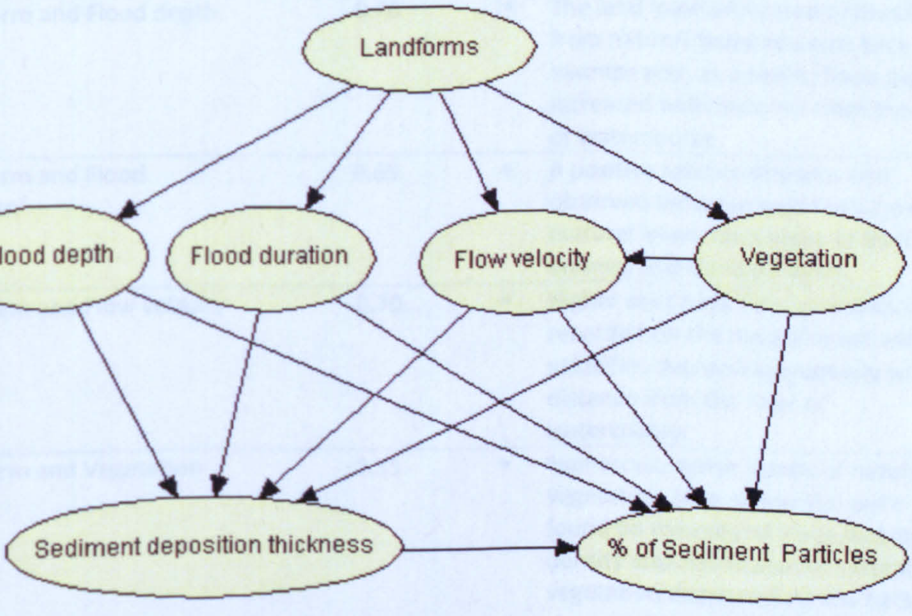


Figure 7.13 Physical model within the BNDSS

Conditional probabilities were calculated to populate conditional probability tables (CPTs) for BNDSS by applying the chain rule arrangement (equations 7.6 to 7.8) for basic probability calculus together with Bayes' Theorem, using the relative frequency of the variables (Pearl, 1988; Castelletti and Soncini-Sessa, 2007; Mount and Stott, 2008). Three, discrete states are possible for each node of the model and the calculated prior and conditional probabilities for each node and state are listed in the corresponding CPT (Tables 7.16 to 7.21).

The physical model is used to predict the thickness and calibre of sediment deposited on the floodplain through belief propagation (BP), which is the computational tool used in a Bayesian network to drive probabilistic inference by employing bottom-up reasoning (backward propagation), top-down reasoning (forward propagation) or both (Castelletti and Soncini-Sessa, 2007). In this study, both forms of reasoning were used. In this regard, the conditional probabilities were entered into the pre-structured Bayesian network (Figure 7.13) within the Hugin graphical user interface to produce the compiled network shown in Figures 7.14 and 7.15. This infers thickness and type of sediment deposited on a given plot of land probabilistically, based firstly on landform and, secondly, flood depth, flood duration, flood flow velocity and vegetation density and abundance.

Table 7.15 Conditional dependencies in the physical model

Conditional dependency between the variables	Dependency level (± r)	Justification
Landform and Flood depth	0.70	▪ The land level decreased gradually from natural levee towards back swamps and, as a result, flood depth increased with distance from the river or watercourse
Landform and Flood duration	0.65	▪ A positive relationship was also observed between land form type (natural levee, back slope or back swamp) and flood duration
Landform and Flow velocity	-0.70	▪ Higher over bank flow velocities were recorded on the natural levee with velocities decreasing gradually with distance from the river or watercourse
Landform and Vegetation	-0.55	▪ Numerous, dense stands of natural vegetation (esp. sun grass) were found on the natural levee, but the density and abundance of natural vegetation decreased on the back slope and more so in the back swamps

Table 7.16 Prior probability distributions for landforms in 2007 and 2008

Landforms type	Prior probability
Natural levee zone	0.20
Back slope zone	0.50
Back swamp	0.30

Table 7.17 Conditional probability table for flood depth with respect to landform in 2007 and 2008

Flood depth (cm)	Landforms					
	Natural levee		Back slope		Back swamp	
	2007	2008	2007	2008	2007	2008
Low depth (≤ 60)	0.35	0.50	0.25	0.40	0.15	0.30
Medium depth (60-90)	0.55	0.40	0.60	0.50	0.25	0.40
High depth (≥90)	0.10	0.10	0.15	0.10	0.60	0.30

Table 7.18 Conditional probability table for flood duration with respect to landform in 2007 and 2008

Flood duration (days)	Landforms					
	Natural levee		Back slope		Back swamp	
	2007	2008	2007	2008	2007	2008
Short (≤15)	0.85	0.90	0.15	0.50	0.02	0.25
Medium (15-30)	0.10	0.08	0.75	0.40	0.25	0.50
Long (≥ 30)	0.05	0.02	0.10	0.10	0.73	0.25

Table 7.19 Conditional probability table for flood flow velocity in respect to landform in 2007 and 2008

Flow velocity (m/s)	Landforms					
	Natural levee		Back slope		Back swamp	
	2007	2008	2007	2008	2007	2008
Low velocity (≤0.25)	0.02	0.80	0.20	0.45	0.85	0.90
Medium velocity(0.25-0.50)	0.20	0.15	0.70	0.50	0.10	0.07
High velocity (≥ 0.50)	0.78	0.05	0.10	0.05	0.05	0.03

Table 7.20 Conditional probability table for flood flow velocity with respect to vegetation density in 2007 and 2008

Flow velocity (m/s)	Vegetation density (%)					
	Low density (≤10)		Medium density (10-25)		High density (≥25)	
	2007	2008	2007	2008	2007	2008
Low velocity (≤0.25)	0.17	0.20	0.15	0.25	0.05	0.20
Medium velocity (0.25-0.50)	0.28	0.35	0.35	0.45	0.30	0.30
High velocity (≥ 0.50)	0.55	0.45	0.50	0.30	0.65	0.50

Table 7.21 Conditional probability table for vegetation density with respect to landform in 2007 and 2008

Vegetation Density (%)	Landform					
	Natural levee		Back slope		Back swamp	
	2007	2008	2007	2008	2007	2008
Low density (≤10)	0.02	0.10	0.25	0.30	0.85	0.90
Medium density (10-25)	0.10	0.25	0.70	0.50	0.10	0.08
High density (≥25)	0.88	0.65	0.06	0.20	0.05	0.02

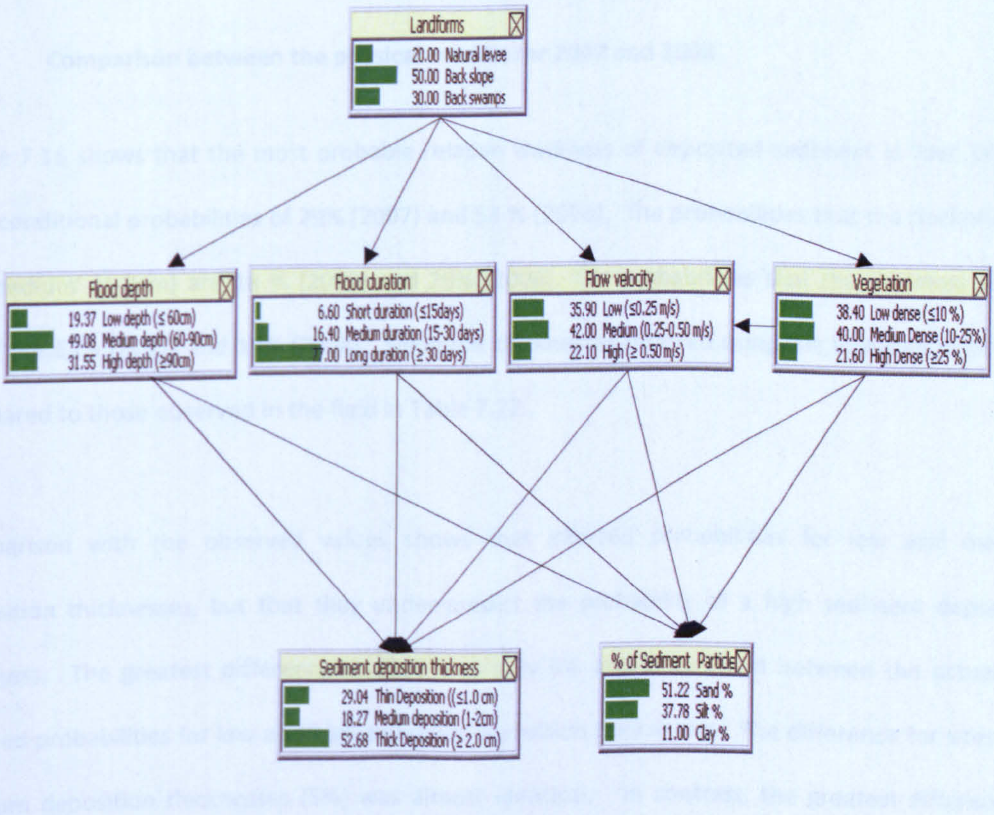


Figure 7.14 Probabilistic outcome of the physical model for sediment accumulation thickness and particle size distribution on the Brahmaputra-Jamuna floodplain during 2007.

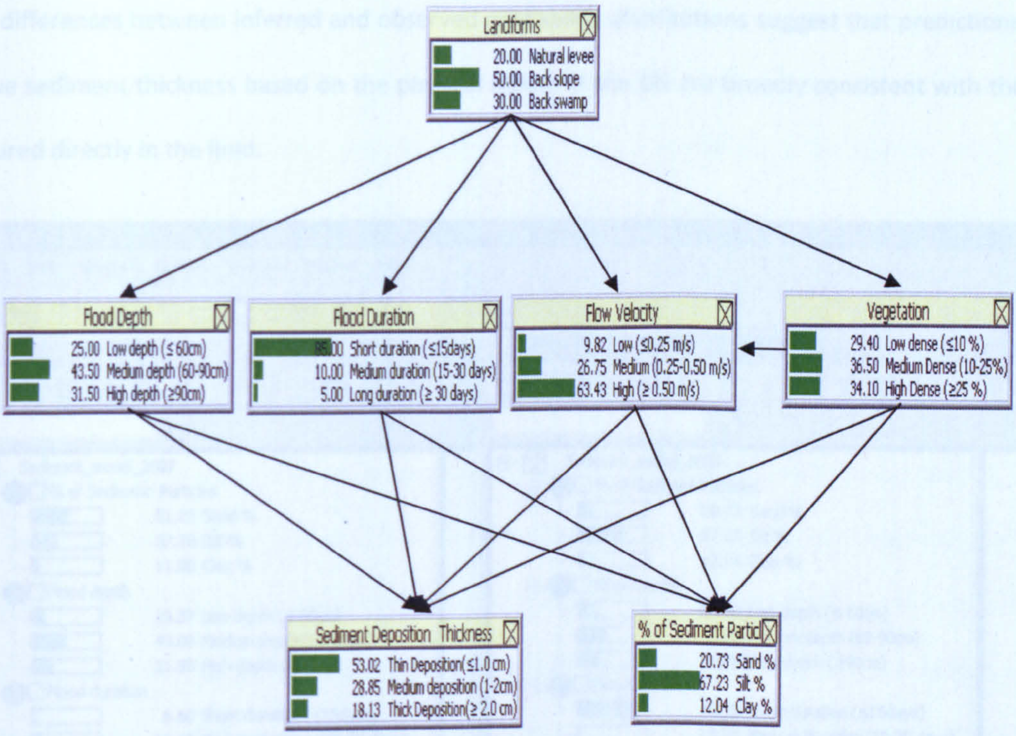


Figure 7.15 Probabilistic outcome of physical model for sediment accumulation thickness and particle size distribution on the Brahmaputra-Jamuna floodplain during 2008.

7.7.1 Comparison between the physical models for 2007 and 2008

Figure 7.16 shows that the most probable relative thickness of deposited sediment is 'low' (≤1cm), with conditional probabilities of 29% (2007) and 53 % (2008). The probabilities that the thickness will be 'medium' (1-2cm) are 18 % (2007) and 29% (2008). The probabilities that the thickness will be 'high' are 53% (2007) and 18% (2008). Sediment thicknesses inferred using the Bayesian network is compared to those observed in the field in Table 7.22..

Comparison with the observed values shows that inferred probabilities for low and medium deposition thicknesses, but that they under-predict the probability of a high sediment deposition thickness. The greatest difference in 2007 was only 6% and it occurred between the actual and inferred probabilities for low and high sediment deposition thicknesses. The difference for sites with medium deposition thicknesses (5%) was almost identical. In contrast, the greatest difference in 2008 (12%) occurred between the actual and inferred probabilities for sites with medium deposition thicknesses, followed by 5% and 4% for high and low deposition sites, respectively. The relatively small differences between inferred and observed probability distributions suggest that predictions of relative sediment thickness based on the physical model in the BN are broadly consistent with those measured directly in the field.

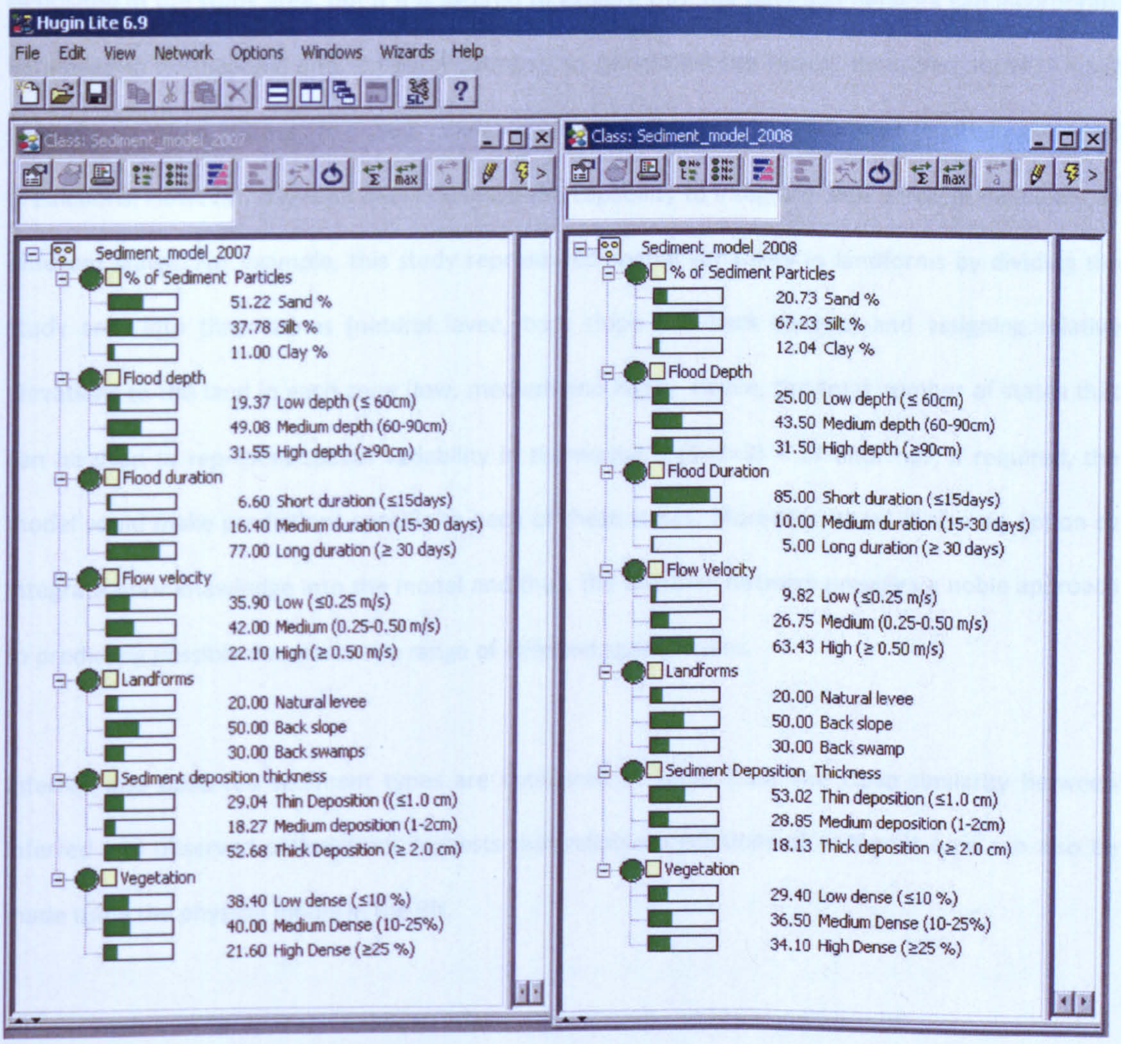


Figure 7.16 Bayesian network for the physical model illustrating probabilistic inferences for 2007 and 2008

Table 7.22 Comparison between inferred (predicted) and observed probabilities for different thicknesses of deposited sediment

Deposition Thickness (cm)	Probability				Difference (± %)	
	Actual P-value		Predicted P-value			
	2007	2008	2007	2008	2007	2008
Thin (≤1cm)	0.31	0.55	0.29	0.53	-6	-4
Medium (1-2cm)	0.19	0.26	0.18	0.29	-5	+12
Thick (≥2cm)	0.5	0.19	0.53	0.18	+6	-5

According to the model, the most probable sediment type in 2007 was sand (51%), followed by silt (38%) and clay (11%). In contrast, silt (67%) was the most probable type of sediment in 2008, followed by sand (21%) and clay (12%). The fact that the model predicts only the average grain size might seem inadequate given that there is considerable spatial variability in the type of sediment deposited in the study area, but if it is desired to explore this, the Bayesian network can incorporate variability in both spatial and temporal contexts. In generating the results described above, I input spatially-averaged values for each variable; hence, the results represent spatially-averaged predictions. However, Bayesian networks have the capability to integrate with different variability, in different states. For example, this study represented spatial variability in landforms by dividing the study area into three zones (natural levee, back slope and back swamp) and assigning relative elevations to the land in each zone (low, medium and high). Hence, the total number of states that can be used to represent spatial variability in the model is (3×3×3) = 27 and thus, if required, the model could make predictions specific to each of these states. Moreover, there is also an option to integrate prior knowledge into the model and thus, the Bayesian network provides a noble approach to predicting possible outcomes at a range of different spatial scales.

Inferred and observed sediment types are compared in Table 7.23. The close similarity between inferred and observed probabilities suggests that reliable predictions of sediment type can also be made using the physical model in the BN.

Table7.23 Comparison between inferred (predicted) and observed types of deposited sediment

Sediment types (%)	Probability				Variation (± %)	
	Actual	P-value	Predicted	P-value		
	2007	2008	2007	2008	2007	2008
Sand	0.48	0.22	0.51	0.21	+6	-5
Silt	0.40	0.65	0.38	0.67	-5	+3
Clay	0.12	0.13	0.11	0.12	-8	-8

Farmers in the study area usually rely on qualitative assessment of sediment deposition thickness and grain size (based on their own vernacular knowledge) when making land use decisions. For example, the 2007 flood was abnormally large and farmers believed that it would generate thicker than usual deposits of coarse grained (sand dominant) particles.

Conversely, in 2008 the flood was thought to be normal and their perception was it would deposit smaller amounts of finer grained (silt dominant) particles. In this context, the quantitative data from the sediment plots validate the farmers' beliefs. However, access to accurate, quantitative information could assist farmers in making decisions based on the type and thickness of fresh sediment and improve the chances of making the right decision with respect to agricultural land use. Thus, the grain size information output by the physical model is consistent with farmers' vernacular knowledge (that is: it will be accepted by them based on their own experience and beliefs) and it could be used as an additional, useful input to their decision-making.

7.7.2 Example applications of the physical model

Each year during the pre-monsoon season farmers are aware of the possibility that the coming monsoon flood may be unusually large and they must consider the risks to their crop yields should an abnormal flood (*bonna)* event occur. The sediment model in the Bayesian Network could assist them in doing this, as it supplies answers to critical queries concerning the most probable thickness and type of sediment that may be expected on any particular plot for a given type of flood (*barsha* or *bonna*). It can do this through top-down reasoning (forward propagation), which involves computing the conditional probabilities of nodal states (i.e. flood depth, flood duration, flow velocity and vegetation density) for a plot of land at a specified distance from the river and then inferring the thickness and particle size distribution (percentage of sand, silt, and clay) of deposited sediment, probabilistically.

For example, in using the BN to infer the probable sediment impact of an extreme flood event, sediment deposition thickness (d) is the child node of flood depth (δ), flood duration (η), flood flow velocity (ν) and vegetation density (ρ). Farmers generally believe that a large flood will generate a thick deposition of sediment (d_h). For a plot located a short distance from the river (on the natural levee), the flood depth is expected to be low (δ_l), the duration short (η_s), and the flow velocity (ν_h) and vegetation density (ρ_h), both high.

According to the Bayes theorem, we can write the probability equation as:

$$P(\delta_l,\eta_s,\nu_h,\rho_h|d_h)=P(\delta_l,\eta_s,\nu_s,\rho_h,d_h)\Big/P(d_h) \tag{7.9}$$

After selecting the expected combination of the states of the variables and run the BN, the maximum sum propagation value is 0.03. Using equation 7.8, the probability of there being a thick layer of deposited sediment is 0.75 or 75%, given the most likely combination of states, indicating that high deposition is indeed the most likely outcome of a *bonna* flood at a site close to the river, on the natural levee.

Similar inferences can be drawn concerning the most likely sediment deposition thicknesses for plots at medium (back slope) and long (back swamp) distances from the river or for events of other (normal or low) magnitudes.

Farmers are also very interested in the proportion of silt deposited by a flood, in comparison to sand and clay, when making decisions concerning agricultural cropping. Hence, they would also like to know the probability that silt will be the dominant size class in the deposited sediment, should an abnormally high flood occur. The sediment model in the BN can also provide the answer to this question through top-down reasoning (forward propagation) using the expected combination of states among the variables. To do this, "silt" $(\varphi_{si})$is set to as the dominant state in the 'sediment type' node and a maximum sum propagation is performed in the Bayesian network, $P(\varphi_{si})$.

For a plot located a medium distance from the river (i.e. on back slope), the expected states are high flood depth (δ_h), long flood duration (η_l), high flood flow velocity (ν_h), high vegetation density (ρ_h), and high sediment deposition (d_h).

According to the Bayes theorem, we can write the equation as:

$$P(\delta_h, \eta_l, \nu_h, \rho_h, d_h | \varphi_{si}) = P(\delta_h, \eta_l, \nu_h, \rho_h, d_h, \varphi_{si}) \Big/ P(\varphi_{si}) \qquad (7.10)$$

The resulting maximum sum propagation value is 0.05. Following the fundamental rule of Bayes' Theorem, we have divided both sides with $P(\varphi_{si})$ and already know the value of $P(\varphi_{si})$. The BN is then used to compute the most likely combination of the different states of the variables and the maximum sum propagation of $P(\delta_h, \eta_l, \nu_h, \rho_h, d_h, \varphi_{si})$ and the value is found to be 0.021.

Using equation 7.10, the probability of silt particles dominating deposition is 0.42 or 42%, should a large flood occur. These examples show how the physical model in the Bayesian network can provide a logical inference based on any specified combination of the states among the variables.

Bottom-up reasoning can also be used to infer the effects on the nodes in the sediment model for 2007, through backward propagation (see Table 7.24 and Figure 7.17). For example, if a sample of deposited sediment is composed entirely of sand, the probability that the sample came from a plot located on the back slope (a medium distance from the river) is 38%. There is, also a 31% chance that it came from either the natural levee (a short distance from the river) or the back swamp (a long distance from the river).

Alternatively, the model can be used to infer the thickness sediment (low, medium or high) based on the outcome of a specified set of conditional probabilities for the network nodes. For example, during a particular flood, a farmer may believe that his plot is on the natural levee (31%), that sand will be deposited (31%) , that the plot will experience a flood that is of low depth (22%) and short flood duration (7%), with low velocity (35%), and that the vegetation density is low (41%).

In this case, the probability that the thickness of deposited sediment is most likely (probability = 54%) to be high (≥2cm), although there is also a 28% chance that it will be low (≤1cm) and an 18% chance that it will be medium (1-2cm) (Figure 7.17-a). Thus, a probabilistic inference can be drawn for the deposition thickness for a specified flood (2007).

Bottom-up reasoning can similarly be used to address the effects on the nodes in model of the 2008 flood, through backward propagation (Table 7.25 and Figure 7.18). For example, if a sample of deposited sediment is composed entirely of silt, it the highest probability is that it came from a plot located on back slope (63%). There is also a 29% chance that it came from the back swamp, but it is unlikely that it came from natural levee as this probability is only 8%.

The model can also be used to infer the percentages of sediment types (sand, silt and clay) for a specified set of conditional probabilities for the network nodes. For example, during a flood with a low depth (17%), short duration (6%) and low velocity (37%), a farmer may be wish to infer the likely thickness of sediment should silt be the dominant grain size deposited on his plot, which he believes to be located on the natural levee (probability = 31%) and for which he estimates the vegetation density to be low (36%).

In this case, setting the sediment size to 100% silt, it is inferred that the most likely outcome (probability = 58%) is that the silt layer would be thin (≤1cm), although there is a 30% chance that it will be medium (1-2cm). Hence, it is likely that a silt layer would be thin or medium in thickness (88%), and it is unlikely to be thick (≥2cm) (probability = 12%) (Figure 7.18-b).

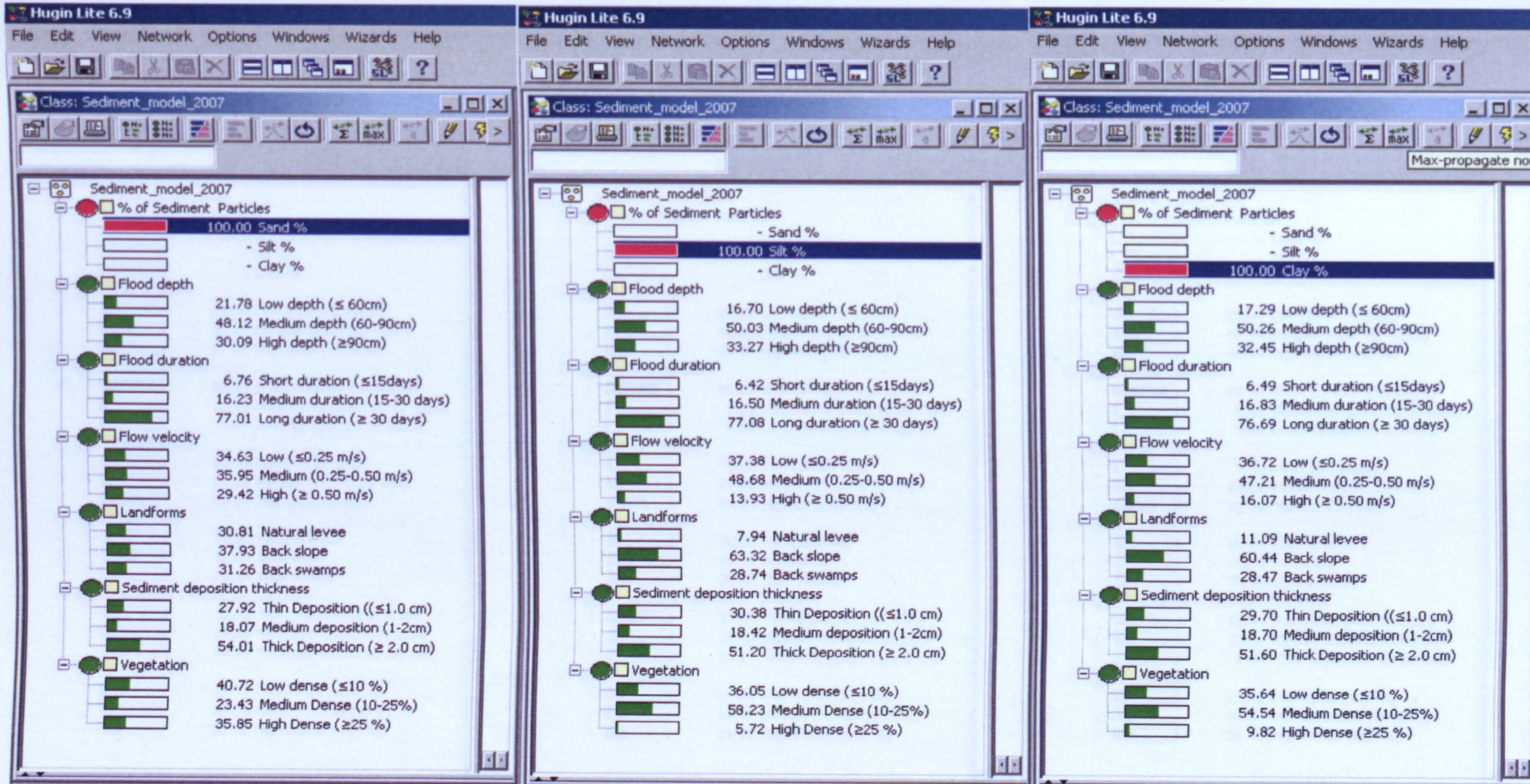
Similar, probabilistic inferences could be drawn for the thickness of sand or clay dominated sediments for floods with any combination of attributes.

Table 7.24 Variation nodal states given that sand, silt or clay are the dominant sediment type (p = 100%) in 2007

Sediment particles (%)	Landforms			Flood depth (cm)			Flood duration (days)			Flow velocity(m/s)			Vegetation (%)		
	Natural levee	Back slope	Back swamp	Low (≤ 60)	Medium (60-90)	High (≥90)	Short (≤15)	Medium (15-30)	Long (≥30)	Low (≤ 0.25)	Medium (0.25-0.50)	High (≥0.50)	Low (≤ 10)	Medium (10-25)	High (≥25)
Sand	0.31	0.38	0.31	0.22	0.48	0.30	0.07	0.16	0.77	0.35	0.36	0.29	0.41	0.23	0.36
Silt	0.08	0.63	0.29	0.17	0.50	0.33	0.06	0.17	0.77	0.37	0.49	0.14	0.36	0.58	0.06
Clay	0.11	0.60	0.29	0.17	0.50	0.33	0.06	0.17	0.77	0.37	0.47	0.16	0.36	0.54	0.10

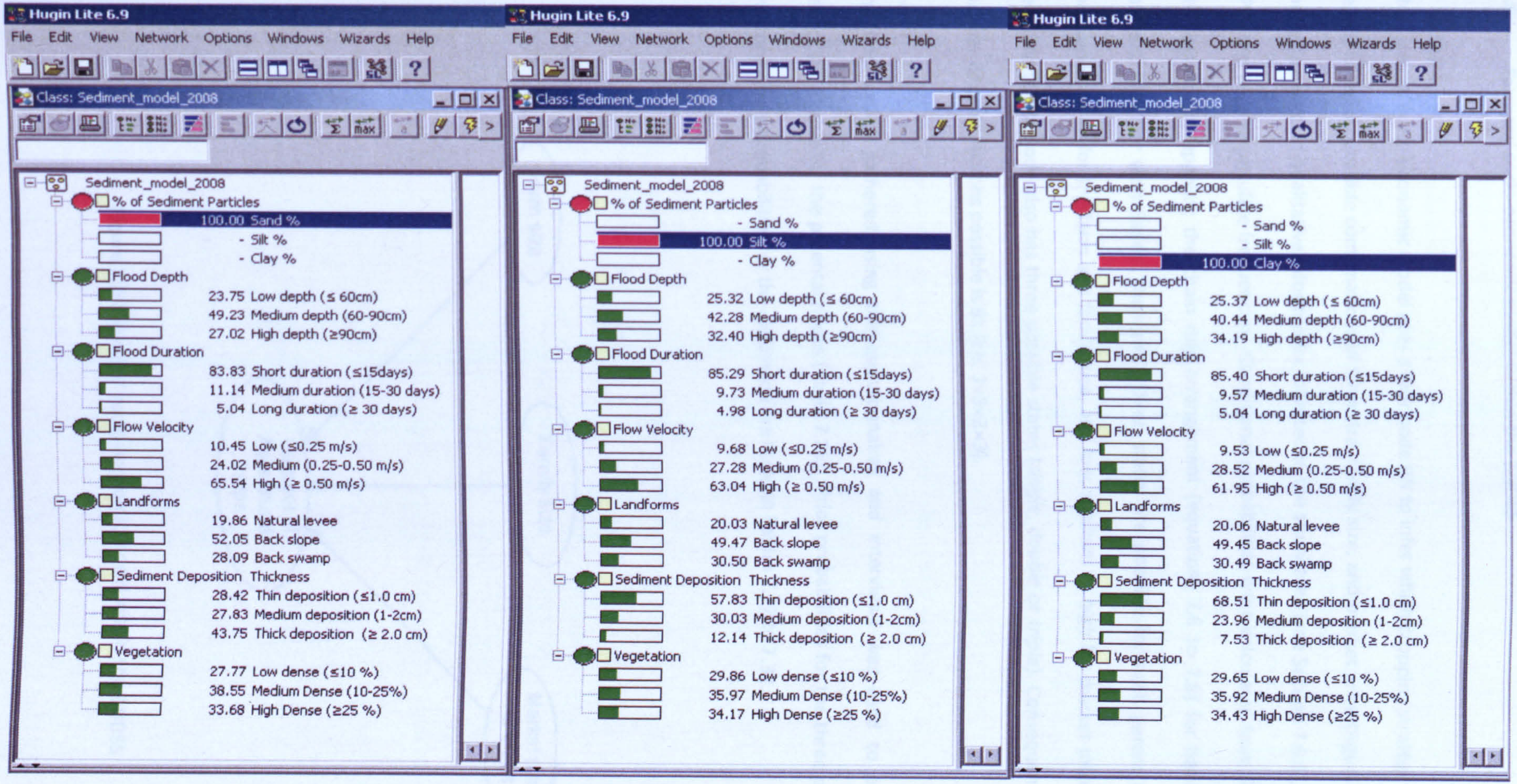
Table 7.25 Variation nodal states given that sand, silt or clay are the dominant sediment type (p = 100%) in 2008

Sediment particles (%)	Landforms			Flood depth (cm)			Flood duration (days)			Flow velocity(m/s)			Vegetation (%)		
	Natural levee	Back slope	Back swamp	Low (≤ 60)	Medium (60-90)	High (≥90)	Short (≤15)	Medium (15-30)	Long (≥30)	Low (≤ 0.25)	Medium (0.25-0.50)	High (≥0.50)	Low (≤ 10)	Medium (10-25)	High (≥25)
Sand	0.20	0.52	0.28	0.24	0.49	0.27	0.84	0.11	0.05	0.10	0.24	0.66	0.28	0.38	0.34
Silt	0.08	0.63	0.29	0.17	0.50	0.33	0.06	0.17	0.77	0.37	0.49	0.14	0.36	0.58	0.06
Clay	0.11	0.61	0.28	0.17	0.50	0.33	0.06	0.17	0.77	0.37	0.47	0.16	0.36	0.54	0.10



(a) (b) (c)

Figure 7.17 Backward propagation (bottom-up reasoning) in the physical model of the Bayesian network for 2007: (a) 100% sand, (b) 100% silt and (c) 100% clay deposition (where a probability of 100% indicates that particles of that type dominate the size distribution of deposited sediment.



(a) (b) (c)

Figure 7.18 Backward propagation (bottom-up reasoning) in the physical model of the Bayesian network for 2008: (a) 100% sand, (b) 100% silt and (c) 100% clay deposition (where a probability of 100% indicates that particles of that type dominate the size distribution of deposited sediment.

7.8 Farmers' socio-economic model within the BNDSS

The farmers' socio-economic model uses a four node BN to infer which cropping strategy a farmer will select, based on possible combinations of farm size, family size, and market price (Figure 7.19). This model is based on qualitative information collected in the study area (see Section 7.6.5), coded using SPSS and used to calculate frequencies. Conditional probabilities were calculated from the frequency distributions by applying the chain rule arrangement (equations 7.6 to 7.8) for basic probability calculus, together with Bayes' Theorem. Three states are possible for each parent node (*small, medium* or *large* for the farm and family size, and *low, medium* or *high* for market price). The crop selection (child) node also has three possible states (*single, double* or *triple*). Consequently, the total number of combinations possible is 81 (i.e. 3×3×3×3).

The information gathered using the questionnaires and interviews was used to populate the dependency table for the parental nodes (Table 7.26). Prior probabilities for the three parent nodes and conditional probabilities for the child node are listed in Tables 7.27 to 7.32.

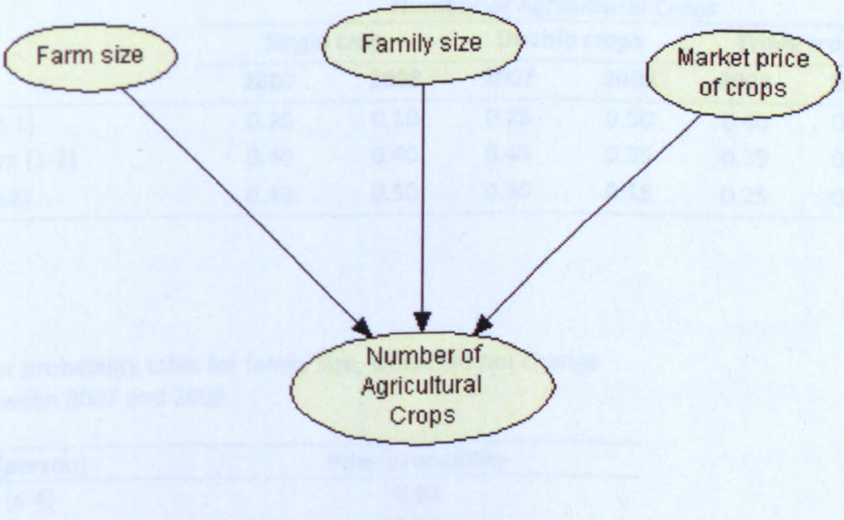


Figure 7.19 Farmers' socio-economic model within the BNDSS

Table 7.26 Conditional dependent probabilities between each of the parent nodes and the child node in the socio-economic model

Conditional dependency between the parent and child nodes	Dependency level (± r)	Justification
Farm size and Number of crops	-0.65	▪ Small and medium sized farm holders usually prefer double and triple cropping, while large farm holders use the land for single and double crops.
Family size and Number of crops	0.85	▪ Large and medium sized families rely on subsistence crops and prefer to cultivate double or triple crops, while small families prefer cash crops and follow a single or double cropping strategy.
Market price and Number of crops	0.70	▪ Higher prices stimulate all types of farmers to adopt a double or triple crop strategy.

Table 7.27 Prior probability table (PPT) for farm size, which did not change between 2007 and 2008

Farm size (ha)	Prior probability
Small farm (≤ 1)	0.64
Medium farm (1-2)	0.30
Large farm (≥2)	0.06

Table 7.28 Conditional probability table (CPT) for number of agricultural crops with respect to farm size in 2007 and 2008

Farm size (ha)	Number of Agricultural Crops					
	Single crop		Double crops		Triple crops	
	2007	2008	2007	2008	2007	2008
Small farm (≤ 1)	0.20	0.10	0.25	0.50	0.40	0.60
Medium farm (1-2)	0.40	0.40	0.45	0.35	0.35	0.30
Large farm (≥2)	0.40	0.50	0.30	0.15	0.25	0.10

Table 7.29 Prior probability table for family size, which did not change between 2007 and 2008

Family size (person)	Prior probability
Small family (≤ 4)	0.68
Medium family (5-7)	0.24
Large farm (≥8)	0.08

Table 7.30 Conditional probability table (CPT) for number of agricultural crops with respect to family size in 2007 and 2008

Family size (person)	Number of Agricultural Crops					
	Single crop		Double crops		Triple crops	
	2007	2008	2007	2008	2007	2008
Small family (≤ 4)	0.10	0.05	0.15	0.05	0.10	0.05
Medium family c	0.30	0.30	0.35	0.35	0.30	0.10
Large farm (≥8)	0.60	0.65	0.50	0.60	0.60	0.85

Table 7.31 Prior probability table for relative market price of agricultural crops in 2007 and 2008

Relative market price of crops (%)	Prior probability	
	2007	2008
Low (≤ 25)	0.05	0.02
Medium (25-50)	0.30	0.20
High (≥50)	0.65	0.78

Table 7.32 CPT for number of crops with respect to relative market price of agricultural crops in 2007 and 2008

Relative market price of crops (%)	Number of Agricultural Crop selection					
	Single crop		Double crops		Triple crops	
	2007	2008	2007	2008	2007	2008
Low (≤ 25)	0.10	0.05	0.10	0.05	0.10	0.02
Medium (25-50)	0.20	0.15	0.25	0.20	0.15	0.10
High (≥50)	0.70	0.80	0.65	0.75	0.75	0.90

The CPTs were entered into the pre-structured Bayesian network (Figure 7.19), and the model was run to produce the probabilistic inferences shown in Figures 7.20 and 7.21. Double cropping was the most likely outcome in 2007, with a probability of 38%, though triple cropping was almost as likely (p = 36%) that year. Single cropping was less likely in 2007 (p = 26%). In 2008, triple cropping was clearly the most probable outcome (p = 67%), followed by double cropping (p = 24%). However, the probability that a single crop strategy will be selected in 2008 was only 9%. Comparison of these inferred (predicted) probabilities with the relative frequencies based on what was actually observed in the field reveals a remarkable similarity (Table 7.33).

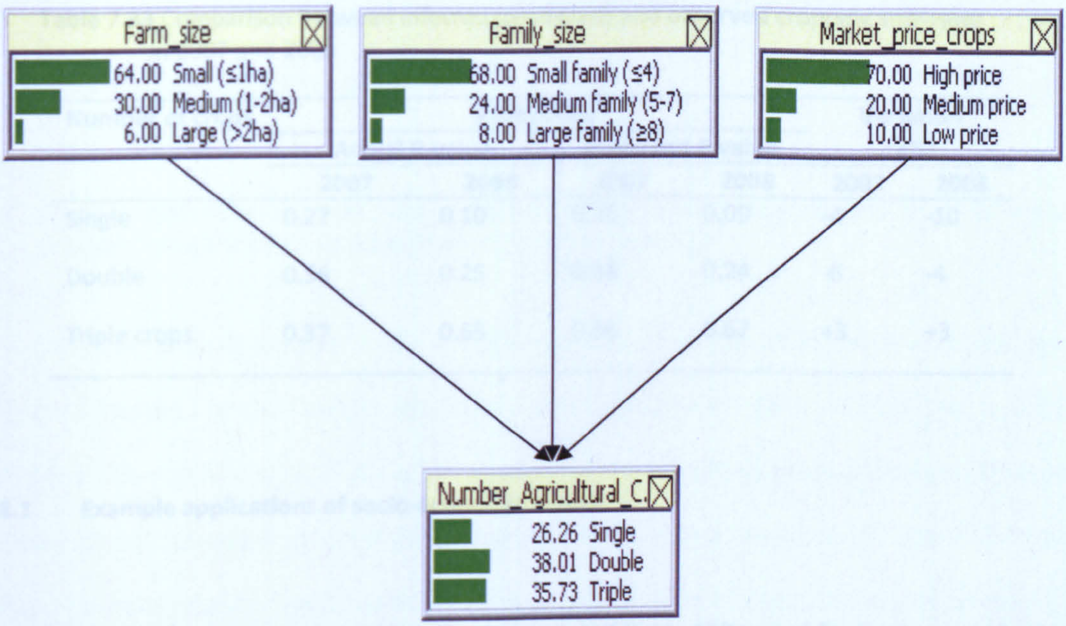


Figure 7.20 Probabilistic inferences for the number of agricultural crops cultivated annually based on farm size, family size and the relative market price of crops in 2007

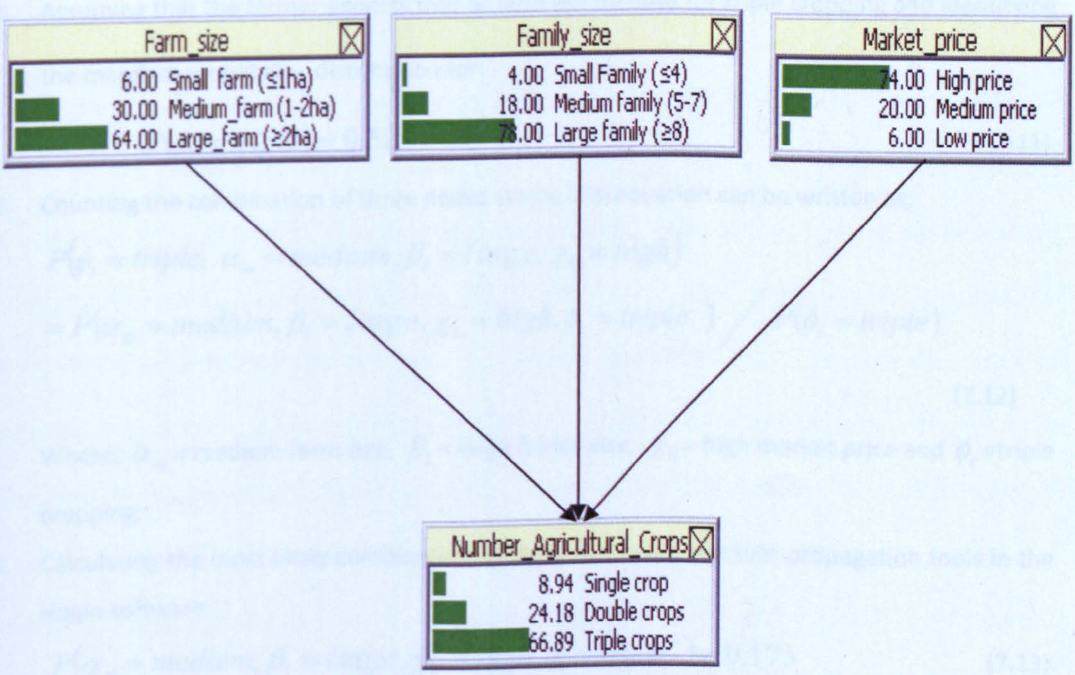


Figure 7.21 Probabilistic inferences for the number of agricultural crops cultivated annually based on farm size, family size and the relative market price of crops in 2008

Table 7.33 Comparison between inferred (predicted) and observed cropping strategies in 2007 and 2008

Number of crops	Probability				Variation (±%)	
	Actual P-value		Predicted P-value			
	2007	2008	2007	2008	2007	2008
Single	0.27	0.10	0.26	0.09	-4	-10
Double	0.36	0.25	0.38	0.24	-6	-4
Triple crops	0.37	0.65	0.36	0.67	+3	+3

7.8.1 Example applications of socio-economic model

A farmer might wish to check the probability that a plot of land will be used for three crops given the prior conditions that the farm size is medium, the family size is large and market prices are relatively high. To check this, the propagation tools for the BN were used to compute the combination of states and count the possible results by:

1. Assuming that the farmer expects that all land will be used for triple cropping and identifying the marginal probability distribution for:

$$P(\phi_t = triple) = 0.52 \tag{7.11}$$

2. Counting the combination of three nodes states, the equation can be written as;

$$P(\phi_t = triple | \alpha_m = medium, \beta_l = large, \chi_h = high)$$
$$= P(\alpha_m = medium, \beta_l = large, \chi_h = high, \phi_t = triple) \Big/ P(\phi_t = triple) \tag{7.12}$$

Where, α_m = medium farm size, β_l = large family size, χ_h = high market price and ϕ_t =triple cropping.

3. Calculating the most likely combination of the states using the sum propagation tools in the Hugin software:

$$P(\alpha_m = medium, \beta_l = large, \chi_h = high, \phi_t = triple) = 0.175 \tag{7.13}$$

4. Solving equation 7.12, the expected probability for triple cropping on a plot of land = 0.175/0.52 = 0.34

This analysis infers that the probability that a plot of land will be used for three crops given the specified conditions is 34%. Any of the other 80 possible combinations of nodal states within the BN can similarly be evaluated to make a probabilistic inference concerning the cropping strategy (single, double or triple) that a farmer may select for a given plot of land, depending on interaction of the three socio-economic variables (parent nodes).

7.9 Creating a Bayesian network decision support system (BNDSS) for optimal land use decision making through the construction of an Influence Diagram (ID)

The preceding sections have described the Bayesian Networks that drive the physical and socio-economic models. In this study, utility and decision nodes were added to these BNs to provide additional information and so improve the reliability of the inferences, leading to development of a Bayesian Decision Support System (BDSS) in the form of an Influence Diagram (ID) (Oliver and Smith, 1990). The states of utility and decision nodes are seldom associated with the marginal probability of the discrete chance node; rather they act in deterministic and mutually exclusive ways because they are derived from the expert knowledge of the decision maker. Utility and decision nodes are displayed according to the convention used in the graphical user interface, within which a decision node is represented as rectangle and a utility node as a diamond.

Every year, farmers must decide on the use to which they put a plot of land based on the need to meet the family's demand for food and depending on whether crop prices are high, so that any surplus can return a profit. This usually results in a desire to cultivate multiple crops (particularly paddy; multiple crops in a year namely, *aus, aman* and *boro* or IRRI). They also try to assess the suitability of the land for multiple cropping, which varies seasonally, depending on the calibre of sediment deposited on it during the monsoon flood (i.e. the percentages of sand, silt and clay). However, this decision is seldom easy to make. For example, a farmer may desire to cultivate multiple crops due to the socio-economic situation, even though the soil is unsuitable or sandy sediment is likely to be deposited on the land so that there is a high probability that the yield from multiple cropping will be far below the optimum yield that could have been achieved for that plot. Hence, it is imperative for a farmer to consider the risk (probability of making a poor choice) when deciding how to use his land. Currently, the great majority of farmers rely solely on their expert knowledge when making these decisions, and combining this Vernacular Knowledge (VK) with the two outcomes of the

Bayesian Networks (BNs) constituting the physical and socio-economic models should improve the reliability of the decision support provided by the resulting BNDSS/ID.

Figure 7.22 shows a four-node BNDSS representing the land use decision-making process. Here the decision node, *Land use*, has two child nodes: *Sediment type (% of sand, silt and clay)*, *Number of crops (single, double and triple)* and one utility node; *Farmers' Vernacular Knowledge* (i.e. farmers' long term experience in matching the number of crops to the suitability of the land). Given that farmers always hope to cultivate double or triple crops annually to support their family food demand and generate some income from selling surplus crops, the decision to be tested is whether selecting multiple rather than single cropping is likely to be good, OK or bad, in terms of productivity. In this context, the utility node (VK) provides additional information based on prior knowledge that can assist the farmer in judging whether a decision to plant multiple crops is likely to be sound. Thus, it allows the famer's VK to influence the outcome, in addition to the two state variables, *Sediment type,* and *Number of crops.*

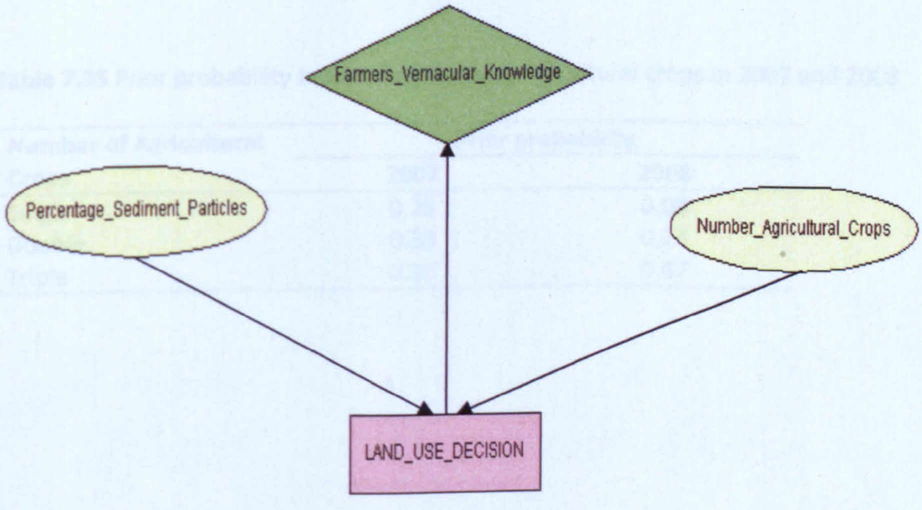


Figure 7.22 Bayesian Network Decision Support System (BNDSS) for agricultural land in the form of an Influence Diagram (ID)

In this example, decision node *Land use* (∂) (i.e. the decision to cultivate multiple crops annually) has three potential states: *good* (∂_g), *OK* (∂_o) and *bad* (∂_b). The discrete chance nodes each have three possible states. *Sediment type* (φ) is made up of *sand* (φ_s), *silt* (φ_{si}) or *clay* (φ_c), in any combination, based on their percentages in the particle size distribution. The number of crops (ϕ) may be *single crop* (ϕ_s), *double crop* (ϕ_d), or *triple crop* (ϕ_t). Thus, BNDSS includes 27 (3×3×3) possible combinations of states, each with its own conditional probability. Prior probabilities must be specified for the discrete chance nodes representing *sediment type, number of crops* and the utility node representing *farmer's knowledge*. Based on the prior probabilities output by the physical and socio-economic models, CPTs were computed using Bayes' theorem (Tables 7.34 and 7.35), based on their relative frequencies. The CPT for the decision node, *Land use* was then computed (Tables 6.35 to 6.38). This CPT defines the probabilistic relationship between the three key variables in the model.

Table 7.34 Prior probability table for sediment particles (%) in 2007 and 2008

Sediment Particles (%)	Prior probability	
	2007	**2008**
Sand	0.51	0.21
Silt	0.38	0.67
Clay	0.11	0.12

Table 7.35 Prior probability table for number of agricultural crops in 2007 and 2008

Number of Agricultural Crops	Prior probability	
	2007	**2008**
Single	0.26	0.09
Double	0.38	0.24
Triple	0.36	0.67

7.9.1 Model-1 (Physical model for 2007 and farmer Socio-economic model for 2007)

After calculating the CPTs (Table 7.36), the BNDSS was run to produce the inferred outcomes (Figure 7.23). The results show that, in the study area, given that the sediment deposited in 2007 was 51% sand, 38% silt and 11% clay, and socio-economic conditions indicated that the probabilities of the three possible cropping strategies in 2007 were: single crop 26%, double crops 38% and triple crops 36%, then the probability of a decision on using the land for multiple crops being bad was 51%.

There was a 28% chance that a decision would be OK, but only a 21% chance that it would be good. These results illustrate that if the land is vulnerable to sand deposition due to the occurrence of a large flood but the farmers still prefer to go for multiple crops in that year, then there is a better than even chance that choosing to plant double or triple crops will be a bad decision.

Table 7.36 Conditional probabilities calculated for the utility node (farmers' vernacular knowledge) based on their perceptions concerning relative frequencies of sediment types (% of sand, silt and clay particles) and number of agricultural crops cultivated in 2007 (Model-1)

Number of Agricultural Crops	Sediment Types (%)	Probability of land use decision		
		Bad	**OK**	**Good**
Single	Sand	0.55	0.30	0.15
Single	Silt	0.45	0.25	0.30
Single	Clay	0.60	0.20	0.20
Double	Sand	0.65	0.30	0.05
Double	Silt	0.50	0.25	0.25
Double	Clay	0.60	0.25	0.15
Triple	Sand	0.40	0.30	0.30
Triple	Silt	0.45	0.35	0.25
Triple	Clay	0.60	0.15	0.25

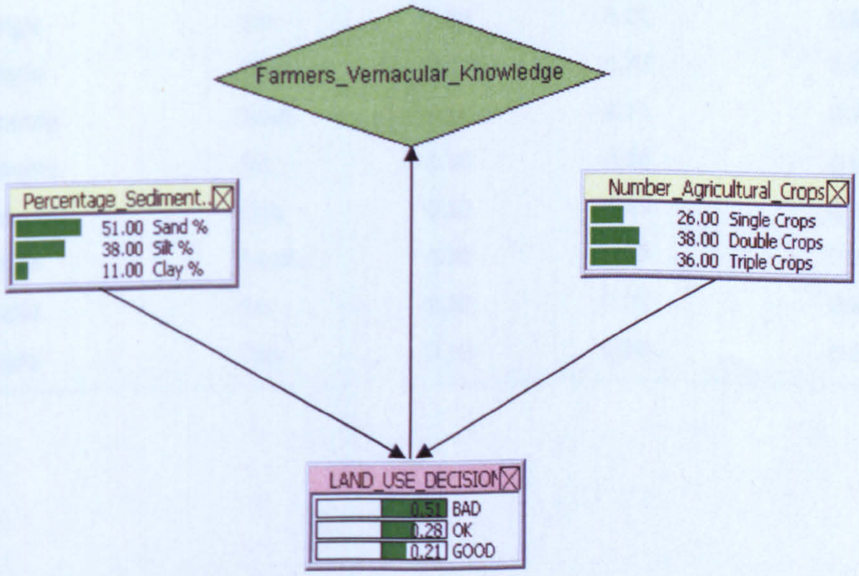


Figure 7.23 Probabilistic inferences concerning the quality of land use decisions given the sediment types and number of crops selected in 2007

7.9.2 Model-2 (Physical model for 2008 and Socio-economic model for 2008)

Using the CPTs (Table 7.37) for Model-2, the predicted outcome is shown in Figure 7.24. The results contrast sharply with those of Model-1. The probability of a decision to go for multiple cropping in a year being good is 66%, OK 24%, and only bad 10% given that the probability of sand deposition is 21%, silt 67% and clay 12%, and that the probabilities of single, double and triple cropping are 9%, 24% and 67%, respectively. The explanation for this contrast is that, because 2008 was a normal (*barsha*) flood year, sediment deposition was dominated by silt, which is better for agricultural crop production. Hence, choosing to plant crops is likely to be a good decision (66%) and is very unlikely to be a bad decision (10%).

Table 7.37 *Conditional probabilities calculated for the utility node* (farmers' vernacular knowledge) based on their perceptions concerning relative frequencies of sediment types (% of sand, silt and clay particles) and number of agricultural crops cultivated in 2008 (Model-2)

Number of Agricultural Crops	Sediment Types (%)	Probability of land use decision		
		Bad	OK	Good
Single	Sand	0.10	0.20	0.70
Single	Silt	0.05	0.10	0.85
Single	Clay	0.10	0.20	0.70
Double	Sand	0.10	0.15	0.75
Double	Silt	0.10	0.30	0.60
Double	Clay	0.10	0.25	0.65
Triple	Sand	0.10	0.20	0.70
Triple	Silt	0.10	0.25	0.65
Triple	Clay	0.10	0.30	0.60

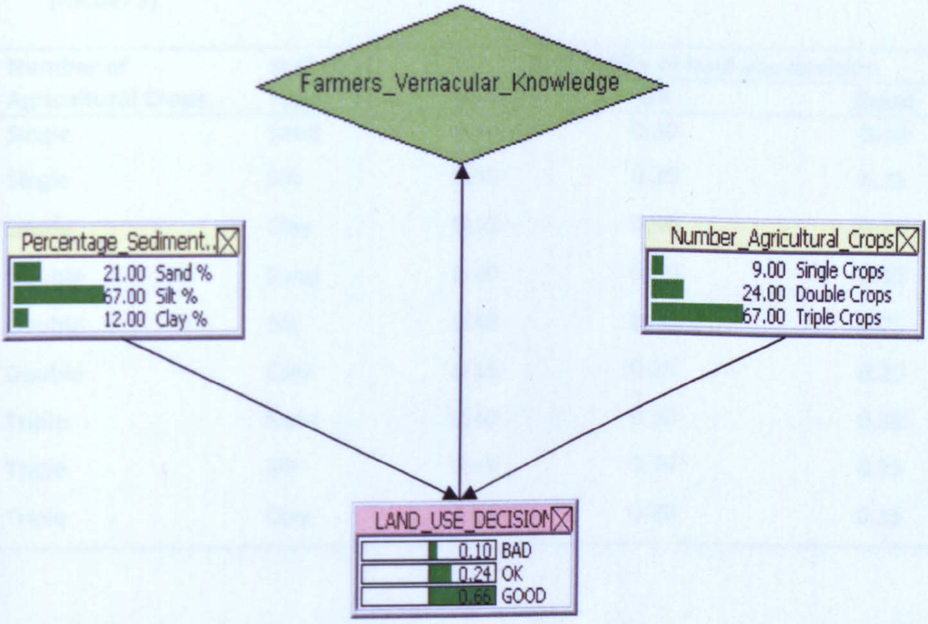


Figure 7.24 Probabilistic inferences concerning the quality of land use decisions given the sediment types and number of crops selected in 2008

7.9.3 Model-3 (Physical model for 2007 combined with the Socio-economic model for 2008)

This scenario explores what the outcome would be if a farmer used a cropping strategy based on the outcome of the socio-economic model for a normal (*barsha*) event (2008) but a major (*bonna*) flood produces elevated coarse sediment deposition (2007). The CPTs for this model are listed in Table 6.38 and the probabilities are shown in Figure 7.25. The results show that the outcome of combining the models in this way is that the probability of a bad decision for multiple cropping is 51%. The chance of a decision being OK is 27% and the probability of making a good is only 22%. These results demonstrate that it is crucial for farmers to evaluate the possibility that coarse sediment may be deposited on their land to avoid a better than evens chance of making a bad land use decision.

Table 7.38 Conditional probabilities calculated for the utility node (farmers' vernacular knowledge) based on their perceptions concerning relative frequencies of sediment types (% of sand, silt and clay particles) in 2007 and number of agricultural crops cultivated in 2008 (Model-3)

Number of Agricultural Crops	Sediment Types (%)	Probability of land use decision		
		Bad	OK	Good
Single	Sand	0.60	0.30	0.10
Single	Silt	0.50	0.25	0.25
Single	Clay	0.55	0.30	0.15
Double	Sand	0.40	0.50	0.10
Double	Silt	0.48	0.30	0.22
Double	Clay	0.55	0.25	0.20
Triple	Sand	0.40	0.30	0.30
Triple	Silt	0.45	0.30	0.25
Triple	Clay	0.65	0.20	0.15

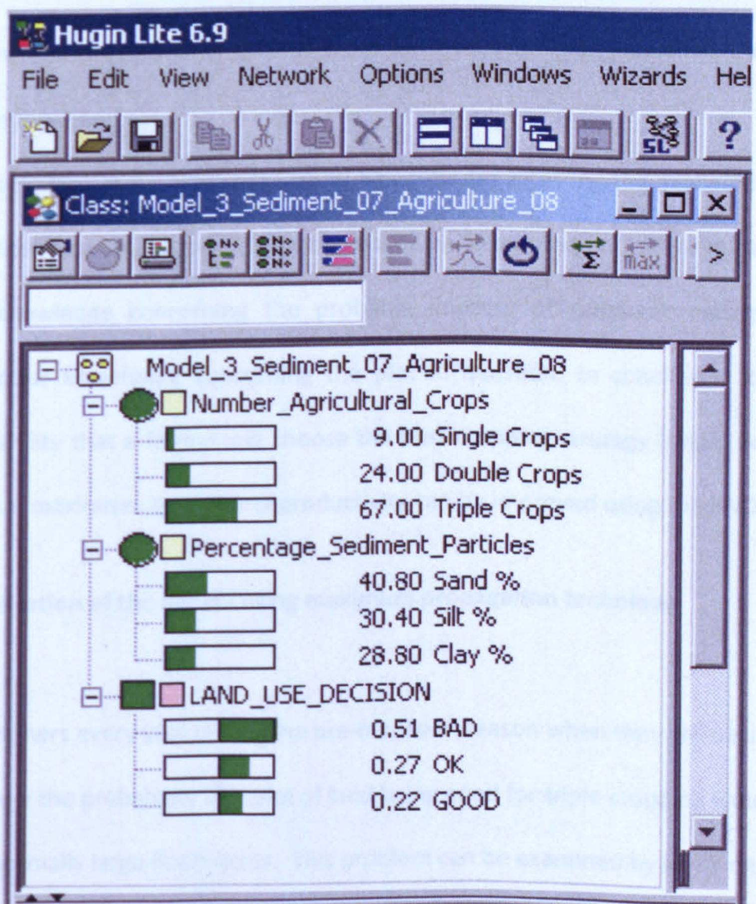


Figure 7.25 Probabilistic inferences concerning the quality of land use decisions given the cropping outcomes for 2008 and the sediment outcomes for 2007

7.9.4 Model-4 (Physical model for 2008 combined with the Socio-economic model for 2007)

In this scenario, the sediment outcomes from 2008 are combined with the crop strategy from 2007 (Table 7..39 and Figure 7.26). The probability of making a bad decision regarding use of a plot for agricultural cropping for multiple crops is 50%. The chance of a decision being OK is 27%, while there is a 23% probability of making a good decision. These results demonstrate that it is crucial for farmers to evaluate the possibility that abundant silt may be deposited on their land to improve the chances of maximising crop yield. If they anticipate sand, but get silt there is an even chance that they will make a bad land use decision.

The outcomes of the two scenarios represented by model-3 and model-4 illustrate that if farmers choose the number of crops they cultivate based on a sound assessment of their socio-economic circumstances but make a mistake in accounting for the impacts of sediment calibre they are highly likely to make sub-optimal land use decisions. In practice, the situations represented by both model-3 and model-4 are frequently encountered by farmers in the Brahmaputra floodplain. Consequently, farmers make decisions that are bad or only OK most of the time, generating lower that anticipated agricultural yields from their land.

However, the results also hint at how a BNDSS could be useful for inferring the probabilities that a decision to go for multiple cropping is good, OK or bad based on an assessment of land suitability that integrates scientific knowledge concerning the probable impacts of sediment calibre on land suitability with vernacular knowledge concerning the plot in question. In conclusion, the results suggest that the probability that a farmer will choose the best cropping strategy (single or multiple) for a given plot land that maximises agricultural productivity can be improved using the BNDSS.

7.9.5 Example application of the BNDSS using maximum propagation technique

A crucial issue facing farmers every year during the pre-monsoon season when they are deciding on their crop strategy is how the probability of a plot of land being good for triple cropping would be affected should an abnormally large flood occur. This problem can be examined by inferring the probability of the land being good for triple cropping with sand as the dominant sediment, based on combining the VK, physical and socio-economic models.

Table 7.39 Conditional probabilities calculated for the utility node (farmers' vernacular knowledge) based on their perceptions concerning relative frequencies of sediment types (% of sand, silt and clay particles) in 2008 and number of agricultural crops cultivated in 2007 (Model-4)

Number of Agricultural Crops	Sediment Types (%)	Probability of land use decision		
		Bad	**OK**	**Good**
Single	Sand	0.60	0.30	0.10
Single	Silt	0.50	0.25	0.25
Single	Clay	0.40	0.15	0.45
Double	Sand	0.40	0.20	0.40
Double	Silt	0.25	0.35	0.40
Double	Clay	0.55	0.35	0.10
Triple	Sand	0.40	0.30	0.30
Triple	Silt	0.30	0.35	0.35
Triple	Clay	0.30	0.30	0.40

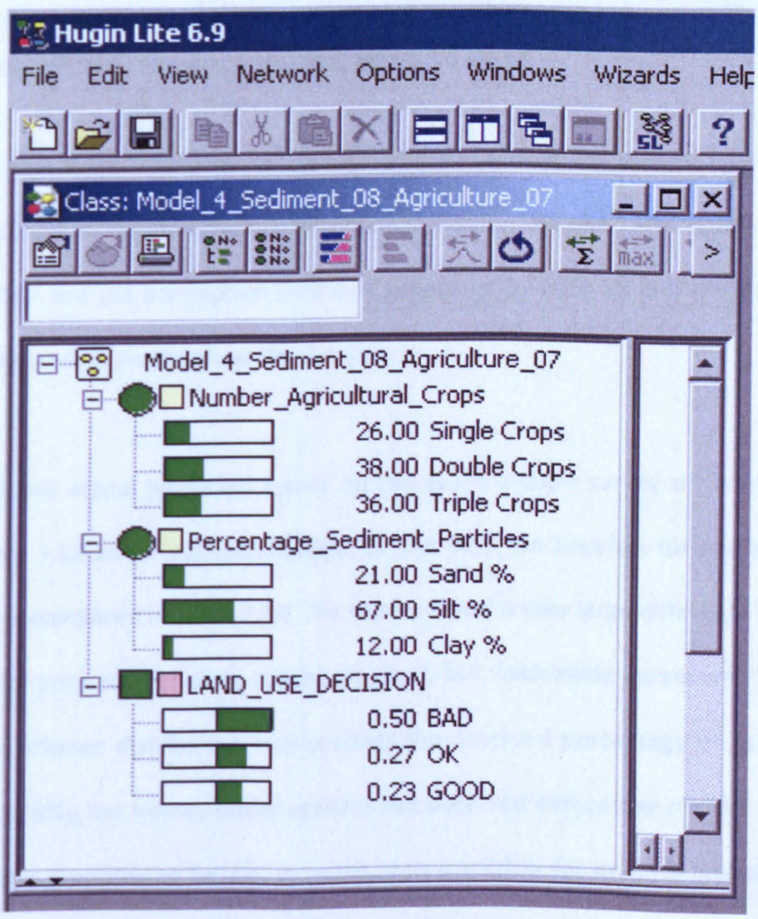


Figure 7.26 Probabilistic inferences concerning the quality of land use decisions given the cropping outcomes for 2007 and the sediment outcomes for 2008

The procedure to achieve this is;

1. *The marginal probability distribution for a decision to cultivate multiple crops (i.e. double or triple)* being *good* may be calculated from the combination of the states giving the maximum propagation:

$$P(\partial_p) = 0.60 \tag{7.14}$$

2. To account for the combination of the three nodal states we can write the equation as;

$$P(\partial_p = high | \varphi_s = sand, \phi_t = triple)$$
$$= P(\varphi_s = sand, \phi_t = triple, \partial_p = high) \Big/ P(\partial_p = high)$$

(7.15)

3. Sum propagation of the most likely combination of the states yields:

$$P(\varphi_s = sand, \phi_t = triple, \partial_p = high) = 0.106 \tag{7.16}$$

4. The probability can be inferred using equation 7.15. This yields the probability for the land being of good for triple cropping = 0.106/0.60 = 0.34 = 0.18

This result suggests that there is only an 18% chance of a plot of land being good suitable for triple crop farming should sand be the dominant sediment deposited on the plot. This calculation is based on the model for 2007 and the assumption (which is supported by both VK and observations), that sand deposition is likely when an abnormal flood occurs.

Inferred (predicted) and actual (observed based on the questionnaire survey of farmers' opinion; section 7.6.5.4, Table 7.12 and 7.13) probabilities for the land use decision for multiple cropping (good, OK or bad) are compared in Table 7.40. The results reveal a very large difference for decisions as 'bad', a large difference for decisions classed as good, but reasonable agreement for decisions classed as 'OK'. The inferred distribution over-predicts the observed percentage of 'good' multiple cropping decisions (+26%), but heavily under-predicts the observed percentage of 'bad' ones (-56%). The proportion of land predicted to be 'OK' in terms of its suitability for multiple cropping is slightly under-predicted (-9%) compared to the information derived from the farmers' VK. This suggests that the farmers' understanding of the suitability of land for multiple cropping could be improved through integration of scientific information with their expert knowledge.

Table 7.40 Differences in land use decisions for multiple cropping based on questionnaire survey and inferred using the BNDSS for 2007 and 2008

Land use Decision	Probability		Difference (%)
	Actual P-value	Predicted P-value	
Bad	0.18	0.08	- 56
OK	0.32	0.29	-9
Good	0.50	0.63	+26

A BNDSS represents a novel approach to supporting decision making through probabilistic inference, though it is under used in fluvial applications (Mount and Stott, 2008). In this context, the BNDSS developed in this study is no more than a prototype in that by no means all of the physical and human factors that affect agricultural land use on floodplains are taken into account. In fact, the BNDSS presented here includes only the most fundamental factors that affect agricultural land use decision making. Consequently, the confidence in the results may be questioned. Nevertheless, the results are achieved logically and there is reasonable agreement between the observed and inferred outcomes. One possible way of improving confidence n the results might be by adding more utility variables. Conditional probability tables can be constructed based on expert opinions, and the same analysis can be conducted for combinations of states through backward and forward propagation to evaluate the reliability of the expert knowledge. In addition, the BNDSS presents the results as conditional probabilities of the potential variables that can be directly interpreted as a causal effect in taking decisions. This raises the possibility of using the BNDSS to integrate observations and expert knowledge and so generate better information on land suitability for agriculture.

7.10 Using the BNDSS in Practice

The preceding sections report the development of a Bayesian Network Decision Support System (BNDSS) demonstrate how it can be used to evaluate land use decision making (good, OK or bad) in a probabilistic manner in the context of two distinct types of flood event (2007 – abnormally high and 2008 - normal). It is evident from the results that land use decisions were much better in 2008 compared to 2007.

It is has also been shown that a thorough understanding of influence of the variables can be obtained through back propagation (bottom-up reasoning) using the BNDSS. In practice, farmers would, of course, prefer that 100% of their land use decisions were good. However, uncertainty in the measured values of the variables and natural variability in the characteristics of flood events mean that this is, in reality, impossible. Despite this, it is possible (and in fact essential) to use the BNDSS to explore the influence which variables actually exert on the quality of agricultural decision making, so that research can be focused on reducing uncertainty and improving the reliability of the most important factors. This should make it easier for end users to make good decisions. In this section, two states of land use decision (good and bad) are considered, because end user need to know which variables are most strongly linked to whether a decision is good or bad. Figure 7.27 presents the overall BNDSS.

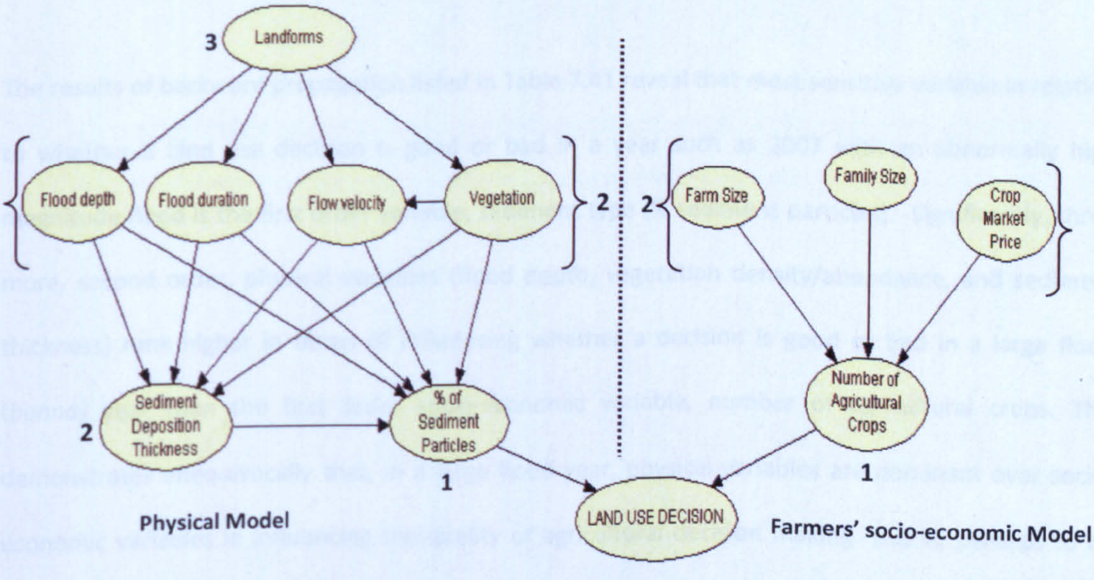


Figure 7.27 BNDSS formed through combination of Physical and socio-economic models (Numeric figures indicate the dependency order).

The variables in BNDSS have grouped into three dependency orders: first order (percentage of sediment particles and number of agricultural crops); second order (flood depth, flood duration, flow velocity, vegetation, sediment deposition thickness, farm size, family size and crop market price), and; third order (landform type) (Figure 7.27).

Backward propagation can be used to trace changes in the states of the variables that occur when the assumption that land use decisions are 100% good is replaced with the assumption that they are 100% bad, for each of the two floods that were studied. The results for 2007 and 2008 are presented in Figures 7.28 and 7.29, respectively. A total of four cases have been investigated: a) 2007 with decision making = 100% good; b) 2007 with decision making = 100% bad; c) 2008 with decision making = 100% good, and; d) 2008 with decision making = 100% bad. To illustrate the changes in the states of the variables, the results of the four different combinations for the quality of decision-making and the type of flood are presented and compared directly in Tables 7.41 and 7.42.

Case1: Good versus bad decision making in large (*bonna*) flood year: 2007

The results of backward propagation listed in Table 7.41 reveal that most sensitive variable in relation to whether a land use decision is good or bad in a year such as 2007 with an abnormally high magnitude flood is the first order variable, sediment type (% sediment particles). Significantly, three more, second order, physical variables (flood depth, vegetation density/abundance, and sediment thickness) rank higher in terms of influencing whether a decision is good or bad in a large flood (*bonna)* year than the first order socio-economic variable, number of agricultural crops. This demonstrates unequivocally that, in a large flood year, physical variables are dominant over socio-economic variables in influencing the quality of agricultural decision making. This is, perhaps to be expected given the results of the field studies on the dominance of flood and sediment dynamics during a catastrophic flood event, though the importance of natural vegetation under these circumstances is, perhaps, surprising.

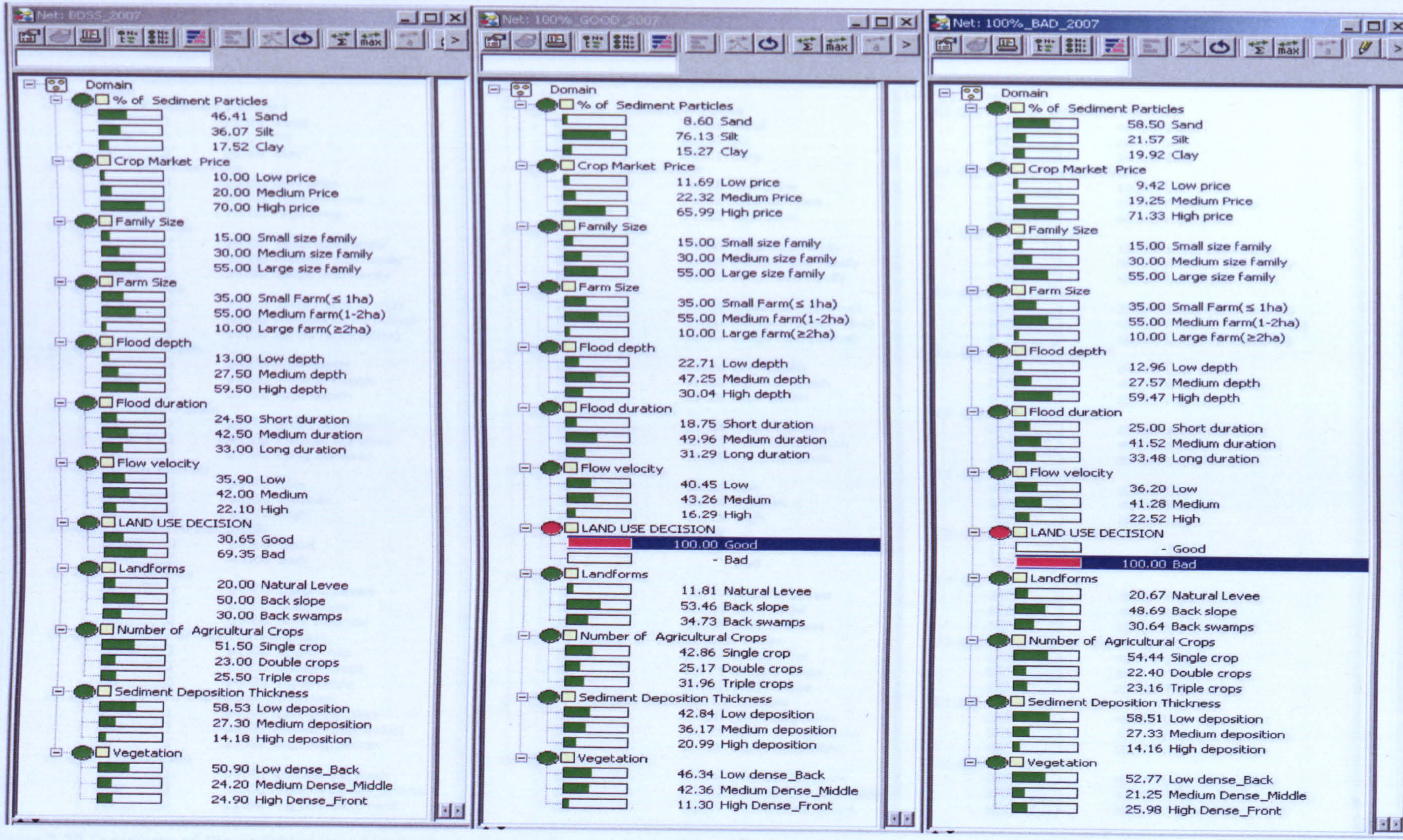


Figure 7.28 Sensitivity of the variables found by back propagating for decision making set equal to 100% good versus 100% bad in 2007

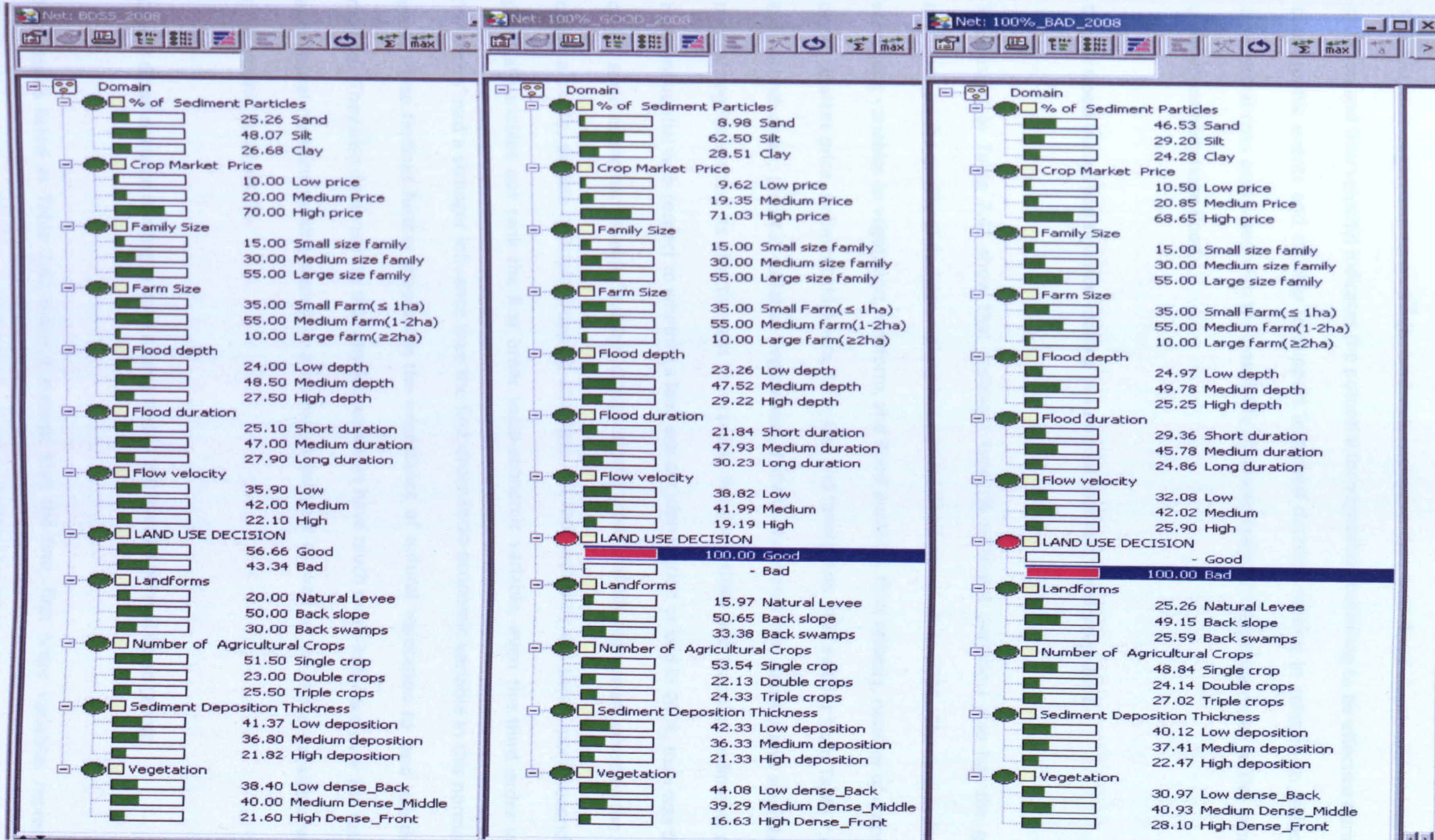


Figure 7.29 Sensitivity of the variables found by back propagating for decision making that is set to 100% good versus 100% bad in 2008

The fact that vegetation ranks 3rd (behind only sediment type and flood depth and ahead of flood duration and flow velocity) indicates the potential for vegetation buffering to be effective during even catastrophic events and so help to support improved decision making in relation to reducing the agricultural risks associated with the possibility of coarse sediment deposition due to the occurrence of an abnormally large flood.

Case2: Good versus bad decision making in a normal (*barsha*) flood year: 2008

The results in Table 7.41 show that sediment type (% sediment particles) also has the greatest influence on the quality of decision making in a normal flood year such as 2008. The rank order of the remaining variables is: vegetation, landform, and flood duration, flow velocity, number of crops, flood depth, market price, sediment thickness, farm size and family size. It is evident from Table 7.41 that the second order, physical variable 'vegetation', (which represents the density and abundance of natural vegetation and its effectiveness in retarding flood velocities and trapping sediment) was far more influential with respect to whether a land use decision is good or bad in 2008, than was the first order, socio-economic variable 'number of agricultural crops' (which represents whether the farmer chose a single, double or triple cropping strategy). In fact, not only did three more second order physical variables out rank the first order socio-economic variable, even the third order variable 'landform' had a stronger influence than the first order socio-economic variable in this normal flood year. These findings further emphasise the importance of natural vegetation to land use decision making. They also demonstrate that physical variables have much more influence over the quality of agricultural decision making during in a normal flood year as well as on those occasions when a catastrophic flood occurs.

Case-3 Good decision making in both a large flood (2007) and a normal flood (2008)

The results listed in Table 7.42 make it evident that the two, first order variables representing sediment types (% sediment particles) and cropping strategy (number of crops) have the greatest influence over making good decisions concerning agricultural land use when both large and normal flood years are considered together. However, the second order variables 'vegetation' and 'crop market price' also play important roles. Interestingly, the third order variable 'landform' is more influential than any of the other second order variables (flood duration, flow velocity, flood depth, sediment deposition thickness, farm size and family size). These findings demonstrate that making good decisions requires that the farmer takes careful account of both physical and socio-economic factors regardless of whether a normal or a large flood occurs. They again emphasise the influence of vegetation and, hence, the potential for natural vegetation to be used pro-actively in reducing the probability that a plot may be damaged by coarse sediment deposition and so increase the probability that a farmer's decision on cropping strategy will turn out to have been a good one in terms of optimising crop yield.

Case-4 Bad decision making in both a large flood (2007) and a normal flood (2008)

It is evident from the results in Table 7.42 that with respect to bad decision making in either large or normal flood years, second order, physical variables (flood depth, vegetation and sediment thickness) dominate the sensitivity ranking. These are followed by the first order, physical variable representing sediment type (% sediment particles), and another second order, physical variable (flood duration). The highest ranked socio-economic variable is the first order variable 'number of crops'. Landforms, flow velocity, crop market price, farm size and family size complete the rankings. Clearly, bad decisions result from inadequate or inaccurate consideration of the possible impacts of physical variables related to the magnitude and dynamics of the flood and the character of the sediments (especially the thickness) it deposits on the land. This demonstrates that while making good decisions (Case-3) requires a thorough understanding of both physical and socio-economic factors, bad decisions can be avoided if farmers take careful account of the physical factors affecting their plots. As in the previous three cases, the density and abundance of natural vegetation ranks very highly (second) in importance. The constantly high ranking of vegetation across all four cases may be surprising, but it demonstrates that natural vegetation strongly influences flood and sediment dynamics and reinforces the message that vegetation can be used to improve the reliability of land

Table 7.41 Identification and ranking of variable sensitivity to good and bad land use decision making in large (2007) and normal (2008) flood years

Dependency Order	Variable	Variable States	2007					2008				
			100% Good	100% Bad	Diff.	Sum Root Sq. Diff.	Sensitivity Rank	100% Good	100% Bad	Diff	Sum Root Sq. Diff.	Sensitivity Rank
1st Order	% Sediment Particles	*Sand*	8.6	58.5	49.9	108.9	**1**	9.0	46.5	-37.6	75.1	**1**
		Silt	76.1	21.6	-54.4			62.5	29.2	33.3		
		Clay	15.3	19.9	4.6			28.5	24.3	4.2		
	No. Agricultural Crops	*Single*	42.8	54.4	12.4	24.0	**5**	53.5	48.8	4.7	9.4	**6**
		Double	25.2	22.4	-2.8			22.1	24.1	-2.0		
		Triple	32.0	23.2	-8.8			24.3	27.0	-2.7		
2^{nd} Order	Flood Depth	*Low*	22.7	13.0	-9.7	58.8	**2**	23.3	25.0	-1.7	7.9	**7**
		Medium	47.3	27.6	-19.7			47.5	49.8	-2.3		
		High	30.0	59.4	29.4			29.2	25.3	4.0		
	Flood Duration	*Short*	18.8	25.0	6.2	16.9	**7**	21.8	29.4	-7.5	15.0	**4**
		Medium	50.0	41.5	-8.5			47.9	45.8	2.2		
		Long	31.3	33.5	2.2			30.2	24.9	5.4		
	Flow Velocity	*Low*	40.5	36.2	-4.3	12.4	**8**	38.8	32.1	6.7	13.5	**5**
		Medium	43.2	41.3	-1.9			42.0	42.0	0.0		
		High	16.3	22.5	6.2			19.2	25.9	-6.7		
	Vegetation	*Low Dense*	46.3	52.8	6.5	42.2	**3**	44.1	31.0	13.1	26.2	**2**
		Medium Dense	42.4	21.3	-21.1			39.3	40.9	-1.6		
		High Dense	11.3	25.9	14.6			16.6	28.1	-11.5		
	Sediment Thickness	*Thin*	42.8	58.5	15.7	31.4	**4**	42.3	40.1	2.2	4.4	**9**
		Medium	36.2	27.3	-8.9			36.3	37.4	-1.1		
		Thick	21	14.2	-6.8			21.3	22.5	-1.1		
	Farm Size	*Small*	35.0	35.0	0.0	0.0	**10**	35.0	35.0	0.0	0.0	**10**
		Medium	55.0	55.0	0.0			55.0	55.0	0.0		
		Large	10.0	10.0	0.0			10.0	10.0	0.0		
	Family Size	*Small*	15.0	15.0	0.0	0.0	**10**	15.0	15.0	0.0	0.0	**10**
		Medium	30.0	30.0	0.0			30.0	30.0	0.0		
		Large	55.0	55.0	0.0			55.0	55.0	0.0		
	Crop Market Price	*Low*	11.7	9.4	-2.3	10.6	**9**	9.6	10.5	-0.9	4.8	**8**
		Medium	22.3	19.3	-3			19.4	20.9	-1.5		
		High	66	71.3	5.3			71.0	68.7	2.4		
3^{rd} Order	Landform	*Natural Levee*	11.8	20.7	8.9	17.8	**6**	16.0	25.3	-9.3	18.6	**3**
		Back Slope	53.5	48.7	-4.8			50.7	49.2	1.5		
		Back Swamp	34.7	30.6	-4.1			33.4	25.6	7.8		

Table 7.42 Identification and ranking of variable sensitivity to good land use decision making in 2007 and 2008, and bad decision making in 2007 and 2008

Dependency Order	Variable	Variable States	100% Good					100% Bad				
			2007	2008	Diff.	Sum Root Sq. Diff.	Sensitivity Rank	2007	2008	Diff	Sum Root Sq. Diff.	Sensitivity Rank
1st Order	% Sediment Particles	*Sand*	8.6	9.0	0.4			58.5	46.5	12.0		
		Silt	76.1	62.5	13.6	27.2	**1**	21.6	29.2	-7.6	24.0	**4**
		Clay	15.3	28.5	-13.2			19.9	24.3	-4.4		
	No. Agricultural Crops	*Single*	42.8	53.5	-10.7			54.4	48.8	5.6		
		Double	25.2	22.1	3.1	21.5	**2**	22.4	24.1	-1.7	11.1	**6**
		Triple	32.0	24.3	7.7			23.2	27.0	-3.8		
2nd Order	Flood Depth	*Low*	22.7	23.3	-0.6			13.0	25.0	-12.0		
		Medium	47.3	47.5	-0.2	1.6	**8**	27.6	49.8	-22.2	68.3	**1**
		High	30.0	29.2	-0.8			59.4	25.3	34.2		
	Flood Duration	*Short*	18.8	21.8	-3.0			25.0	29.4	-4.4		
		Medium	50.0	47.9	2.1	6.2	**6**	41.5	45.8	-4.3	17.3	**5**
		Long	31.3	30.2	1.1			33.5	24.9	8.6		
	Flow Velocity	*Low*	40.5	38.8	1.7			36.2	32.1	4.1		
		Medium	43.2	42.0	1.2	5.8	**7**	41.3	42.0	-0.7	8.2	**8**
		High	16.3	19.2	-2.9			22.5	25.9	-3.4		
	Vegetation	*Low Dense*	46.3	44.1	2.2			52.8	31.0	21.8		
		Medium Dense	42.4	39.3	3.1	10.7	**3**	21.3	40.9	-19.6	43.7	**2**
		High Dense	11.3	16.6	-5.3			25.9	28.1	-2.2		
	Sediment Thickness	*Thin*	42.8	42.3	0.5			58.5	40.1	18.4		
		Medium	36.2	36.3	-0.1	0.9	**9**	27.3	37.4	-10.1	36.8	**3**
		Thick	21	21.3	-0.3			14.2	22.5	-8.3		
	Farm Size	*Small*	35.0	35.0	0.0			35.0	35.0	0.0		
		Medium	55.0	55.0	0.0	0.0	**10**	55.0	55.0	0.0	0.0	**10**
		Large	10.0	10.0	0.0			10.0	10.0	0.0		
	Family Size	*Small*	15.0	15.0	0.0			15.0	15.0	0.0		
		Medium	30.0	30.0	0.0	0.0	**10**	30.0	30.0	0.0	0.0	**10**
		Large	55.0	55.0	0.0			55.0	55.0	0.0		
	Crop Market Price	*Low*	11.7	9.6	2.1			9.4	10.5	-1.1		
		Medium	22.3	19.4	3.0	10.1	**4**	19.3	20.9	-1.6	5.3	**9**
		High	66	71.0	-5.0			71.3	68.7	2.6		
3rd Order	Landform	*Natural Levee*	11.8	16.0	-4.2			20.7	25.3	-4.6		
		Back Slope	53.5	50.7	2.9	8.3	**5**	48.7	49.2	-0.4	10.0	**7**
		Back Swamp	34.7	33.4	1.3			30.6	25.6	5.0		

use decision making, increase the probability that a decision will be good and reduce the chances of making a bad decision.

Exploration of the dependencies and sensitivities of variables in the BNDSS has produced a series of outcomes and rankings that agricultural planners can use to help inform optimum land use in terms of maximising crop yields and reducing the risk of crop damage. The preceding examples, case studies and discussions illustrate how the BNDSS can support probabilistic inference in both directions, through forward and backward propagation, with the potential to play a key role in improved land use decision making. It may, therefore, be concluded that the outcomes of the research reported here could provide the initial basis for enhanced land use planning in the study area based dialogue between agricultural specialists possessing scientific knowledge and local farmers possessing vernacular knowledge.

7.11 Broader implications of the BNDSS for floodplain agricultural land use

In Bangladesh, tens of millions of people depend on agriculture for their livelihoods and the great majority of them farm floodplain land characterised by recurrent flooding and the annual deposition of fresh sediment. It follows that every year these people strive to maximise the agricultural productivity of their land by attuning their selection of crops and cropping strategies to the influences of flood and sediment dynamics, which are highly variable, annually.

Floodplain sedimentation type varies markedly between abnormal (2007) and normal floods (2008). Hence, during the pre-monsoon season, farmers must try to predict whether the coming flood is likely to be above normal, in which case they need to take steps to the reduce the risk of crop damage associated with flooding that is deeper and/or more prolonged than usual and which deposits sediment that is sandy rather than silty. Sound decision making also requires them to be aware of the significance of land elevation and distance from river (characterised by floodplain land type - natural levee, back slope, or back swamp).

These fixed factors influence the probability distributions for flood depth, velocity and sediment type and the sensitivity of these flood characteristics to the magnitude of the event (*bonna* or *barsha*) in any one year. For example, land on the natural levee, close to the river is usually planted with high yield variety (HYV) *aus* paddy during the pre-monsoon season, and lentils, wheat or mustard during the post-monsoon season. Similarly, back slope land is planted with both HYV and local varieties of *aus* and *aman* paddy during monsoon season and lentils, wheat, mustard and varieties of vegetables during the post-monsoon seasons. Back slope land is being mainly cultivated for deep-water paddy during the monsoon and *boro* paddy in post-monsoon season. However, if farmers believe that a *bonna* flood may be imminent, they may co-cultivate *aus* and *aman* paddy to guard against the risk of losing their rice crop and, should an extreme flood cause a thick deposition of sand, farmers may leave land fallow to allow it to recover its fertility or even cultivate peanuts or *sesbania* to enhance fertility. On the other hand, if sedimentation rates are lower and silt is deposited during the monsoon flood, farmers try to take advantage of this by planting lentils, mustard, vegetables, wheat, or maze as *rabi* crops. Many farmers recognise the effects of vegetation on flood velocities and sediments and seek to use their vernacular knowledge to influence flood and sediment dynamics in and around their plots. Some farmers do this by planting buffer strips of sun grass to trap the coarse grain sediments before it enters their fields while others (reluctant to give up any land that could be used for food crops) plant *aman* paddy or sugarcane to slow the floodwaters and encourage finer sediment to settle out. It is also clear that farmers have profound vernacular knowledge concerning soil taxonomy and that they classify soils with respect to their suitability for growing different crops in ways that are adaptive to local circumstances, although their approach is limited in term of sustainability. However, while farmers make extensive use their vernacular knowledge as the foundation for their agricultural planning and practices, they make very limited use of scientific knowledge.

This study included exploration of whether decision making in arable farming at the local scale could be improved based on scientific knowledge generated through geographical analysis of the results of field investigations and monitoring in an area of the Brahmaputra-Jamuna floodplain. The approach adopted employs an Influence Diagram as a Bayesian Network Decision Support System (BNDSS) that interlinks causal relationships amongst the variables using conditional dependencies, that allow users to make land use decisions based on inferring optimum floodplain land use decisions for specified flood dynamics, sediment characteristics and socio-economic factors. Conditional dependencies in the BNDSS developed here are based on field data and information specific to the study area. However, as conditions in the study area are representative of those in the floodplain more generally, the approach could have wider applicability and, therefore, potential importance to decision making on floodplain agricultural land throughout Bangladesh. Even in areas where the data and information collected from the study area are inapplicable, conditional probabilities appropriate to that area could be generated easily by eliciting the necessary information from local farmers and agricultural experts.

However, farmers require simple and practical approaches to decision making with respect to agricultural crop selection and cropping strategies that are easily accessible to them. The results of the interviews conducted in this study show that many farmers (especially subsistence farmers) are not only illiterate, they are also unwilling to rely on governmental and non-governmental bodies, even though they recognise that expert advice based on scientific information concerning flooding, sediment, markets and optimising the selection of crop and cropping strategy for a particular plot in a particular season could be beneficial to them. The BNDSS provides a suitable platform for bringing together vernacular and scientific knowledge, because IDs support the farmer in making a decision rather than trying to make the decision for him. They do not pretend to be 'all knowing' or deterministic, instead making probabilistic inferences of land use suitability for the agricultural crops that inform decision making without taking control of the decision making process, to provide a useful resource for the farmer. Thus, farmers can use them to explore the probable outcomes and risks associated with any number of possible flood events, sediment impacts, and crop selections.

The investigations underpinning the dependencies modelled in the ID have established how agricultural land use suitability depends (amongst other things) on the characteristics of flood-borne sediment deposits. It follows that better decisions concerning crop selection and the number of crops sown annually could be made if reliable, scientific knowledge concerning spatial and temporal variability in sediment attributes, based on routine monitoring, were available to assist farmers in making those decisions. This study has demonstrated how sedimentation can successfully be monitored for very little cost, using low technology approaches. The study has also revealed a paucity of information on sedimentation on the floodplains of Bangladesh. Nevertheless, there appears to be no reason that such monitoring could not be performed routinely nationwide, with the results disseminated to local administrators (at union or *parisad* levels), village leaders, and farmers via government soil and agricultural bodies.

In conclusion, application of scientific knowledge on sediment dynamics to support improved decision making through the use of BNDSS platforms could and should be encouraged in Bangladesh, at farmers' schools and through 'farmers first' training initiatives similar to those available provided around the world in other LEDCs (Cain *et al.*, 2003; Aalders, 2008).

CHAPTER 8 CONCLUSIONS, APPRAISAL OF TECHNIQUES AND FURTHER WORK

8.1 Summary of main findings

Research presented in the preceding chapters of this thesis adopts an integrated approach between natural (sedimentation and vegetation) and human (farmers) processes. This study has explored contemporary floodplain sedimentation, interactions between sediment, vegetation and agricultural land use, and developed a Bayesian Decision Support System (BDSS) to assist farmers in taking decision for agricultural land use of *Bara Bania Mouza (village)* under *Daulatpur Uazila* in *Manikgong* district of the Brahmaputra-Jamuna floodplain in Bangladesh.

The research design encompassed a range of spatial (e.g., natural levee, back slope and back swamp) and temporal scales (2007 and 2008 floods) and employed different scientific methods in an attempt to explore causal relationships among the variables and so present probabilistic inferences. *Bara Bania Mouza* (village) was selected as the study site because it is on the young and active floodplain, where the land surface receives overbank sediment deposition every year - even when a low magnitude flood event occurs. The people who live there are mostly subsistence farmers who, lacking governmental support for their livelihoods, adapt to flooding indigenously, cultivating their land for agriculture based mostly on vernacular knowledge acquired and handed down through the centuries.

The data collected relate to two distinct types of monsoonal flood, e.g., *bonna* (abnormal flood in 2007) and *barsha* (normal flood in 2008). Vegetation indexing of the floodplain includes both homestead and agricultural fields in different seasons and variations of agricultural cropping during pre-monsoon, monsoon and post-monsoon seasons in 2007 and 2008. Data related to rain-fed flooding and sediments were derived only from the normal flood year (2008) because in 2007, the whole study site was flooded by river water due to abnormal flood and hence, there was no area left to represent rainwater-flooding characteristics.

A general Bayesian decision support system was developed to investigate land use decision making for agricultural crops through integration of sub-models for natural processes (sedimentation) and farmers' perceptions of socio-economic factors. The Bayesian Network was used to investigate how the addition of access to scientific knowledge to the existing vernacular knowledge could assist farmers in making better decisions concerning agricultural land use and cropping strategies.

Based on this work, the following conclusions can be drawn with respect to the research questions set out in Chapter One.

8.1.1 Research question one

"How was sediment deposition distributed throughout the study area in 2007 and 2008 and what factors are responsible for this distribution (deposition thickness and particle size distribution)?"

Results presented in Chapter 4 describe contemporary sedimentation and the characteristics of the young and active floodplain typical of the Brahmaputra-Jamuna River in Bangladesh. The quantity and size distribution of sediment deposited on a plot of land depends primarily on its landform setting coupled with the inundation depth, flood flow velocity and flood duration. The topography of the study area (*Bara Bania Mauza*) is subdued with only about 3m of relief between the highest floodplain ridges and the lowest flood basins (*beels*). Based on a DEM developed for the elevation data, the study area can be classified into three main landforms; natural levees (30%, 13.10m-14m) of mainly high to medium high land, the back slope (55%, 11.67m-13.10m) consisting of medium high to medium low land, and back swamps (15%, ≤11.67m), which are low to very low land. This suggests that land of medium elevation dominates the study area and, therefore, that most inundation is likely to be in the 'low' flood depth range.

Flood hydraulics (overland flow velocities, inundation depths and durations) were measured and it was found that these hydraulic variables vary as a function of distance from the nearest river or *Khal*. Suspended sediment concentrations and particle sizes vary with landform zone and distance from the nearest river, with the dominant particle size ranging from fine to medium silt (16μm to31 μm). In 2007 the maximum (4.25g/l) and minimum (1.65g/l) suspended sediment concentrations were measured on the natural levee and in the back swamps (*beels)*, respectively. The equivalent figures were 3.95g/l and 1.25g/l in 2008. These findings indicate that concentrations of suspended sediment were higher in 2007 because of the abnormally high magnitude of the flood (*bonna*) compared to that in 2008, which was a normal flood (*barsha).*

Sediment accumulation thickness also varies with the distance from the river. The thickest deposits were found on the natural levees and thinnest in the back swamps. The thickness of sediment that accumulates in any year depends on the magnitude and duration of the monsoon flood. Consequently, deposits were thicker in 2007 than in 2008 due to the extremely high (abnormal flood) and normal floods which occurred in those years, respectively. These results represent only two years of sediment deposition, but these findings could be further explored for multiple years using other methods such as Caesium^{137} (Stokes and Walling, 2003) to gain insights concerning longer-term rates of sediment accumulation.

Data obtained from marker bed and open excavation experimental approaches have produced sedimentation rates and distributions that are consistent with the results of previous studies performed by ISPAN (1995) and Allison *et al.* (1998). The sizes of sediment grains that accumulated on the floodplain ranged from less than 3.8μm to more than 500μm, (clay to medium sand) across the different landforms in the study area. However, the dominant size was medium silt to very fine sand in 2007 and very fine to coarse silt in 2008. The difference in dominant particle size for the two years was attributed to contrasting flood hydraulics and the effects of micro-scale topographic variability. Sediments were mainly well sorted in both years but most samples were strongly skewed towards the finer fractions and the particle size distributions were extremely leptokurtic (excessively peaked).

These results demonstrate how the characteristics of the floodplain and the hydraulics of the flood are the primary controls on the spatial distribution of sedimentation and the dominant size of deposited particles. Hence, the results and the conclusions presented above answer Research

Question 1 and mean that Research Objectives 1 *"investigation the characteristics of the floodplain study area; hydraulics (over bank flow velocity, flood depth and duration) and land form characteristics)* and 2 *"Examine space and time variations in sedimentation for two monsoon seasons 2007 and 2008"* have been achieved.

8.1.2 Research question two

"How does sedimentation interact with human land use and vegetation? This question has two components:

a. What is the impact of sedimentation (sand/silt or clay) on agricultural land use and how does rainwater flooding, which is sediment-free, contrast with river flooding?

b. How does vegetation (e.g. Sun grass - Imperata cylindrica (Linn.) (Rauschel, Graminea/Poaceae) act to trap sediment?"

Flood and sediment dynamics, especially during unusually large flood events drive significant sedimentation on the floodplain and the results of this study demonstrate that farmers adapt to this by changing agricultural cropping patterns seasonally and annually. For example, in the pre-monsoon season of 2007, 17ha of land were used for single crop cultivation, but this increased to 52ha in 2008. Conversely, 186ha of land were used to cultivate multiple crops in 2007, but this decreased to 151ha in 2008. These changes occurred because land that was cultivated for multiple crops in pre-monsoon of 2007 could only be used for a single crop in 2008 due to the adverse impacts of sand deposited during the 2007 flood event on soil fertility.

Similarly, during the monsoon season in 2007, only 13ha of land were used for single cropping, but this increased to 71ha during the monsoon season in 2008. During this season, the 202ha of land used for multiple crops in 2007 decreased to 143ha in 2008. These results further illustrate the adverse agricultural impacts of sand deposition associated with the 2007 flood.

However, during the post-monsoon season, the area of land that was single cropped decreased in 2008 (12ha) compared to 2007 (33ha), while the area used for multiple crops increased. The explanation of these post-monsoon season land use changes lies in the contrasting impacts of sand deposition in 2007 (which reduced the opportunity to cultivate multiple crops) and silt deposition in 2008 (which increased the opportunity to plant multiple crops).

In conclusion, the results of the field study demonstrate practically that the thickness and calibre of sediment strongly influences farmers' decisions on which and how many crops to cultivate on a given plot. They establish that a close and adaptive relationship exists between the farmers' perceptions of sediment dynamics and their land use decision making on the floodplain in the study area. These conclusions answer the first part of Research Question 2(a) and mean that Research Objective 3 *"Assessing spatial and temporal variation of agricultural land use patterns"* has been achieved.

The field study observed marked contrasts between the characteristics of sediment deposited by rain-fed and river water flooding (Chapter 5). Rainwater collects in floodplain depressions that are usually encircled by medium to high land and inundation occurs due to early monsoon rains during normal flood (*barsha*) flood years. Rainwater is obviously sediment free, but surface runoff erodes soil and the field results revealed that fine-grained sediment (29μm) accumulated at an average rate of 1.7cm/yr in depressions inundated by rain-fed flooding. Rates were higher (2.75cm/yr) with coarser grained sediment (53μm) in areas inundated by river water.

Most farmers are aware of the distinction between rain-fed and river flooding, but most of them prefer river flooding because they think that it brings fresh sediment, which makes the land fertile. However, a limited number of farmers believe rain-fed flooding to be helpful in other ways. This is, in fact, the case for four different reasons. Firstly, the wash load deposited by rain-fed flooding contains more organic matter than the sediment supplied by river flooding because it comes from the surrounding, higher land areas. Secondly, there is lower chance that a high rate of sedimentation or coarse grain size will damage crops or reduce soil fertility. Thirdly, rain-fed floodwater is less turbid than the river water and, hence, light penetrates more effectively. This encourages photosynthesis and the growth of submerged vegetation, and decomposition of crop residues that provides substantial amounts of organic matter at the end of the monsoon season to improve fertility. Lastly, field research found green and blue-green algal mats to be much more extensive in both paddy fields and fallow lands in areas flooded by rainwater. A very few farmers who recognise the benefits of algal mats to soil fertility actually mash and mix these mats with the soil during ploughing but most farmers regard them as weeds and take them away.

These findings support the conclusions of Brammer (1995b) in answering the second part of Research Question 2(a) and achieving Research Objective 4 ("*Contrast the sedimentation characteristics associated with rainwater flooding and river flooding*"). It is apparent that further, in-depth research is needed to fully evaluate the sediment, chemical and biological characteristics of rain-fed flooding, the organic properties of algal mats and the benefits to soil fertility in comparison with those of riverwater flooding.

The dominant vegetation species in study area floodplain is gramineae (60%), followed by amarantaceae (25%), convolvulaceae(10%) and leguminosea (5%), which includes sun grass (*Imperata cylindrica*) on the natural levee, mat grass (*Hemarthria altissima*) on the back slope and cynodon (*Cynodon intermedius*) in the back swamps (Figures 6.17 and 6.18). Amongst these species, natural stands of sun grass (*Imperata cylindrica*, Linn., Gramineae/Poaceae) play a very important role with respect to agricultural land use by acting as buffer strips that trap and filter sediment along the natural levee (Chapter 5). Field results reveal wide variations in sediment deposition thickness inter-annually and between the front, middle, back of these vegetation strips. In 2007, a maximum sediment deposition thickness (4.50cm) was measured in front of a vegetation strip, while the minimum (0.90cm) was recorded behind a vegetation strip. The D_{50} of deposited sediment decreased from 81μm to 28μm and 22μm passing from the front, to the middle and then the back of the sun grass strips. In 2008, the maximum deposition thickness was 3.10cm (measured in front of the strip) falling to a minimum of 0.65cm behind the strips. D_{50} values decreased from 84μm to 31μm and 18μm at the front, middle and back of the stands. While local people cut the sun grass and use it for cattle feed, roofing, fencing and fuel, farmers believe that, as it is a deep-rooted grass, it is harmful to agricultural crops. Many of them remove stands of sun grass to extend their agricultural land. This increases the spatial extent of coarse grained sediment deposition, which spreads across the arable fields and damages crops. In extreme cases, they cannot use the land for crop cultivation in the following seasons. Conversely, if farmers leave the sun grass strips in place along the natural levees, coarse sediment can be trapped, protecting the hinterland from coarse sediment but allowing fine sediment to pass through, which makes the land more suitable for agricultural use (Meyer *et al.*, 1995).

In the pre-monsoon season farmers mainly cultivate shallow water and deep-water rice, jute, sugarcane and *sesbania*. Of these crops, only jute is harvested during the monsoon season, the rest being harvested in post-monsoon season. It was noted in the field survey that the stems of these crops slow floodwater and effectively buffer fields by trapping coarse sediment within a short distance (30-60m) of the field edge. It was also apparent that deep-water rice traps the highest volume of coarse sediment, followed by sugarcane, jute and *sesbania*, respectively. Therefore, farmers who cultivate deep-water rice benefit in two ways. Firstly, they reduce the risk of crop damage by fast flowing floodwater. Secondly, they limit the extend of coarse sediment deposition to the edge of the field while allowing finer particles to pass through to improve soil fertility in the remainder of the plot. These research outcomes are consistent with the findings of Dabney *et al.* (1996).

It may be concluded that both natural vegetation (e.g. sun grass) and certain agricultural crops have huge potential for use in slowing floodwater and trapping sand. The field results demonstrate that buffer strips can be an effective measure to filter coarse sediment during floods, which answers Research Question 2(b) and achieves Objective 5 *"Documentation of vegetation characteristics; identify how vegetation acts to trap sediment, how different grain sizes are affected by vegetated buffer strips"*.

8.1.3 Research question three

"How do farmers account for sedimentation when deciding what crop to grow on a plot of land? Could they make better decisions if they had better information on sedimentation?"

Farmers have profound knowledge based on centuries of observing sedimentation, soil types and agricultural crop associations (Chapter 7). They use their long-held, vernacular knowledge to assess the suitability of the land for cropping based on multiple criteria that include: elevation (landform); soil characteristics and properties (percent sand, silt and clay, structure, drainage etc.); risks associated with fast flowing floodwater and coarse sediment deposition (based on predicting the likelihood that the coming flood might be an extreme event); observations of the flood (magnitude and water colour) as it develops. The outcomes of this study demonstrate that their perceptions and beliefs concur with the results of scientific surveys. For example, in 2007 farmers predicted a high rate of sedimentation, dominated by sand because an abnormally high flood (*bonna*) was expected on the basis that it was nearly a decade since the last catastrophic event. Conversely, in 2008 they predicted a low rate of sedimentation and comparatively finer grain sediment due to their expectation that the flood would be a normal event (*barsha*). The results of field monitoring showed their associations between flood magnitude and sediment thickness/calibre to be correct, while their expectations concerning the type of flood were also sound.

Farmers assess soil type based on observing its colour, rubbing it between the fingers, observing its lumpiness during tilling, tasting the soil, feeling the weight of a handful of soil and throwing water on the soil to test its drainage. It was possible to check the accuracy of the vernacular knowledge of the farmers quantitatively in one respect, based on their estimates of the sand, silt and clay content of each of the soil types. The farmers' estimates proved remarkably accurate, differing by only ±3-15% from the results of scientific particle size analysis. This suggests that the farmers' methods do give reliable indications of key soil attributes.

Farmers in the study area around *Bara Bannia* village use the outcomes of their assessments to classify the soils in the study area into three broad types and six sub types based on their local knowledge of soil texture; *bele maati* (sandy soil), *bele doas maati* (sandy loam soil), *poli maati* (silt soil) *poli doas maati* (silt loam soil) and *aintel maati* (clay soil) and *aintel doas maati* (clay loam soil). In terms of soil quality, farmers recognize the silt loam soil (*poli doas maati*), which is usually found in the upper and lower back slope area(*naal and chwak*) and is the best(*sobcheye bhalo*), being suitable for all types of pre-monsoon, monsoon (*Kharif*) and post-monsoon (*rabi*) crops. The next category is silt soil (*poli maati*), more widely known as (*beshi bhalo*) and found on the upper back slope area (*naal jomi*), which is suitable for both broadcast and transplanted *aus* and *aman* paddy including local and high yield varieties (HYV), jute, sugarcane, oil seeds, wheat and lentils. The sandy loam soil *(bele doas maati)* found adjacent to the levee area and towards the back slope *(danga or kandi),* is recognised as good (*bhalo*) soil suitable for broadcast and *aus and/*or *aman* paddy including local varieties of rice, jute, oil seed, wheat and lentils. Sandy soil (*bele maati*) is of medium quality (*motamoti*) and is found on the natural levee (*nodir teer*). It is suitable only for peanuts, but in some cases farmers grow potatoes, sesame, and *aus* paddy on this soil. The fifth type soil is clay silt (*aintel doas maati*), recognized as marginal to poor (*mondo maati*) that appears in the upper back swamp (*beel*) and seasonal channels crossing the back slope (*khal*). This soil is suitable for HYV *boro* paddy, mustard and lentils. The last category of soil identified by farmers is clay soil (*aintel maati*) which is found in the lower back swamp (*beel*) and is recognized as being very poor (*khub mondho maati*). It is of limited suitability for local varieties of *boro* paddy and mustard.

In Bangladesh as a whole, as well as the study area, farmers are still largely dependent on their own vernacular assessments of soil properties in matching the crops they plant to the suitability of a plot of land. The evidence collected here indicates that although their methods are crude, the results are generally sound. Even so, it is clear that no science is involved in the investigation of soils and sediment properties. It follows that the reliability of these assessments could be improved if scientific information could be integrated with their local knowledge. Improved assessments would provide a better knowledge for farmers needing to select the right crops for a given plot, flood and sediment regime. This would help reduce the risks of crop damage and/or loss of fertility and increase agricultural productivity. These findings answer Research Question 3 and mean that Objective 6 "*Documentation farmers' perceptions on sediment and agricultural land use*" has been achieved.

8.1.4 Research question four

"How do farmers decide on land use more generally and would a Bayesian Network Decision Support System assist them?"

It is evident from the results of the research conducted here that most farmers are subsistence farmers, whose land use decisions are strongly influenced by the imperative to provide family food security. This leads to decisions on whether to cultivate single, double or multiple crops being influenced by family size, farm size (availability of land), and the market prices for different crops (Chapter 7). Farmers who have relatively large families for the amount of land available usually rely on single cropping because it has the lowest risks and guarantees food security even if a major flood event occurs. However, all farmers prefer double or triple cropping, growing *both* food and cash crops to sell at the market in order to generate some income. Consequently, most farmers will go for multiple cropping unless they are prevented from doing so by the poor quality of their land or recently deposited sand that is only sufficiently fertile to support as single crop, such as peanuts.

Farmers are always careful in selecting seasonal crops (Rashid and Pual, 1989) based on their indigenous knowledge of agricultural adjustments to flood dynamics (especially hazards), which have enormous potential for generating optimum yields, on the one hand, or disastrous crop damage, on the other (Haque and Zaman, 1993). Consideration of the risks and benefits associated with flood borne sediments plays a crucial role in land use decision making. To investigate the potential for a Bayesian Decision Support System (BDSS) to assist farmers in making better decisions concerning whether to go for single or multiple crops, this study integrated the results of the physical and socio-economic models to produce probabilistic inferences concerning land use decisions (classing them as *good, OK* or *bad*). Four sets of conditional probabilities were generated and used to investigate the utility of the BNDSS (Chapter 7, section 7.7).

The physical model showed that the most probable relative thickness of deposited sediment is 'low' (≤1cm), with conditional probabilities of 29% (2007) and 53 % (2008). The probabilities that the thickness is 'medium' (1-2cm) are 18 % (2007) and 29% (2008). The equivalent figures for 'high' are 53% (2007) and 18% (2008). These findings indicate that a higher rate of deposited sediment should be expected in large flood year (2007) and that a lower rate is most likely in a normal flood year (2008).

According to the the Bayesian network, the most probable average sediment type deposited in 2007 was sand (51%), followed by silt (38%) and clay (11%). In contrast, silt (67%) was the most probable type of deposited sediment in 2008, followed by sand (21%) and clay (12%). This indicates that silt is likely to be the dominant size of sediment deposited in a normal flood year (2008), but that sand deposition is most likely in a large flood year (2007). These predictions are expressed in terms of the three main types of sediment deposited in the study area because I used just three particle sizes: sand silt and clay, as inputs to the model. In practice, every flood deposits a mixture of several particle size classes rather than sediment of a single type. However, to support improved decision making by farmers in the study area it is only necessary to specify the dominant type of sediment likely to be deposited on their land: i.e. sand, silt or clay. They are not interested in the particle size distribution. The strength of the model is that it informs farmers concerning the probability that sand dominated sediment will be deposited on their land should a high flood occur. Similarly, it communicates to them that the chance of silt being the dominant type of sediment being deposited increases during medium floods. This is important because farmers prefer silt dominant sediments because they are enhance the suitability of their land for agricultural use, in fact, if floods bring fine grain sediment that is considered a blessing. Conversely, farmers are concerned that monsoon flooding may deposit sand on their land as they may have to leave fields fallow for a period after sand deposition. It is for these reasons that better information on the probabilities that sediment of different types will be deposited on their land is very helpful to them. As the great majority of farmers in study area are illiterate, it is vital that information on probable sediment type is delivered in a form that they can understand and incorporate into their decision making. In this context, broad classes of particle size (sand, silt and clay) are appropriate to helping them to make good agricultural land use decisions for the next cropping season.

The socio-economic model showed that double cropping was the most likely outcome in 2007, with a probability of 38%, though triple cropping was almost as likely (p = 36%) that year. Single cropping was less likely in 2007 (p = 26%). In 2008, triple cropping was clearly the most probable outcome (p = 67%), followed by double cropping (p = 24%). The probability that a single crop strategy would be selected in 2008 was only 9%. These results clearly illustrate the preference of farmers to go for multiple cropping.

By integration of physical and farmers' socio-economic models and adding the farmers' vernacular knowledge as prior expert knowledge, the quality of the land use decision to go for multiple crops (double or triple crops annually) was investigated through the Influence Diagram within the Bayesian Network Decision Support System (BNDSS). In the large flood year (2007), 51% of decisions to cultivate multiple crops were *bad* , while in the normal flood year (2008) the probability of this decision proving to be *good* was high (66%).

In practice, BNDSS back propagation results are crucial in identifying the sensitivity of the variables to making good and *bad* decisions concerning agricultural land use. For example, comparison of nodal states for *good* versus *bad* decisions in a large (*bonna*) flood year (2007) demonstrates unequivocally that physical variables dominate over socio-economic variables in influencing the quality of agricultural decision-making. This is, perhaps to be expected given the results of the field studies on the impacts of flood and sediment dynamics on the floodplain environment during a catastrophic flood event.

Similarly, the physical variable 'sediment type' (percentage sediment particles) also has the greatest influence on the quality of decision making in a normal flood year such as 2008. The rank order of the remaining variables is: vegetation, landform, and flood duration, flow velocity, number of crops, flood depth, market price, sediment thickness, farm size and, lastly, family size.

In practice, farmers need to make decisions that are *good* regardless of whether a large flood or normal flood event occurs. In this context, it was evident from the BNDSS that the two, first order variables representing sediment types (% sediment particles) and cropping strategy (number of crops) have the greatest influence over making *good* decisions concerning agricultural land use when both large and normal flood years are considered together. However, the second order variables 'vegetation' and 'crop market price' also play important roles. Interestingly, the third order variable 'landform' is more influential than any of the other second order variables (flood duration, flow velocity, flood depth, sediment deposition thickness, farm size and family size). These findings demonstrate that making good decisions requires that the farmer takes careful account of both physical and socio-economic factors regardless of whether a normal or a large flood occurs.

In case of *bad* decision making in either a large or a normal flood year, second order, physical variables (flood depth, vegetation and sediment thickness) dominate the sensitivity ranking. These are followed by the first order, physical variable representing sediment type (% of sediment particles), and another second order, physical variable (flood duration). Clearly, bad decisions result from inadequate or inaccurate consideration of the possible impacts of physical variables related to the magnitude and dynamics of the flood and the character of the sediments (especially the thickness) it deposits on the land.

Natural vegetation (vegetation density/abundance) turns out to be very important under any circumstances, which is, perhaps, surprising. The fact that vegetation ranks 2nd and 3rd in terms of sensitivity (behind only 'sediment type' and 'flood depth' and ahead of 'flood duration' and 'flow velocity') with respect to a decision to cultivate multiple crops to be *good*, indicates the potential for vegetation buffering to be effective in protecting standing crops during even catastrophic events. It follows that planting buffer strips could help to make the decision to cultivate multiple crops more likely to be a good one, by reducing the possibility of coarse sediment deposition reducing yields due to the occurrence of an abnormally large flood or normal flood.

Exploration of the dependencies and sensitivities of variables in the BNDSS has produced a series of outcomes and rankings that agricultural planners can use to help inform optimum land use in terms of maximising crop yields and reducing the risk of crop damage. The preceding examples, case studies and discussions illustrate how the BNDSS can support probabilistic inferences in both directions, through forward and backward propagation, with the potential to play a key role in improved land use decision making. It may, therefore, be concluded that the outcomes of the research reported here could provide the initial basis for enhanced land use planning in the study area, based dialogue between agricultural specialists possessing scientific knowledge and local farmers possessing vernacular knowledge.

These findings answer Research Question 4 and meet Objective 7 *"Evaluating the effects of sedimentation on human decision-making on agricultural land use"*.

8.2 Appraisal of techniques

The approaches adopted in this research have both strengths and weaknesses. This section considers these in relation to the appropriateness of the techniques employed in each component of the research.

There are a number of techniques available to measure floodplain sedimentation over different time scales, but most are highly technical and expensive to apply, making them infeasible for use in Bangladesh. Hence, this study used a marker bed technique to measure contemporary sedimentation because it was simpler, affordable, required only locally available materials and was easily adaptable. Despite its simplicity, the marker bed method offers the potential to measure sedimentation rates and spatial distributions routinely, to supply quantitative data that can supplement and inform the farmers' vernacular knowledge concerning floodplain sedimentation. That information could help them to decide which and how many agricultural crops to cultivate on a plot of land. Thus, in the context of Bangladesh, marker beds represent an innovative and appropriate technology with which to assess contemporary patterns and rates of floodplain sedimentation.

Sediment deposited across the study area ranged from medium sand to very fine clay particles and therefore use of an LS-coulter counter 230 provides the best approach to particle size analysis. As the technology was available at the University of Nottingham, it was selected for use in this study. However, in Bangladesh, the availability of this technology is currently limited to a few professionals performing PSA for engineering and construction purposes. This is unfortunate as it could be widely employed to improve knowledge concerning spatial and temporal variability in the particle size distributions of contemporary sedimentation in the floodplains of Bangladesh and, thus, inform improved soil zoning for agricultural crop suitability. Increased access to modern PSA technologies should be addressed through initiatives by the appropriate governmental bodies, such as the Soil Resources and Development Institute (SRDI, Bangladesh), perhaps in collaboration with universities and other research organizations in nationally and overseas.

Plot level land use surveys were conducted to determine agricultural land use and land use changes throughout the monsoon floods of 2007 and 2008, the first of which was abnormally high (*bonna*) and the second of which was normal (*barsha*). This was a fortunate outcome because it was the occurrence of two such different floods that allowed me to achieve my study objectives and document how land use dynamics in the study area respond to flood dynamics. However, the short time-scale and local space scale of the study imposes serious limitations on the potential for extrapolating the results and generalising the findings to the entire Jamuna floodplain. The results suggest that land use dynamics are highly responsive locally, but it is likely that changes at the regional scale occur more slowly. Hence, a longer-term data series for a much larger area would be required before it was possible to infer regional or even national land use dynamics. It would not be feasible to collect the necessary data through field work in the way that has been done herein and, of the possible alternatives, high-resolution remote sensing coupled with modern techniques for dating sediments and the use of GIS for spatial and temporal analyses would seem to be the best approach to expanding the scope of the land use and sedimentation studies performed here from the parochial to the regional scales.

In this study, field observations were used to inventory the type, density and diversity of natural vegetation growing in the floodplain. This produces maps that are detailed and accurate, but it is resource intensive both in terms of time and personnel. Potentially, the same surveys could have been performed using remote sensing, but access to aerial Photography is strictly limited in Bangladesh, while acquisition of satellite images of sufficient resolution was infeasible on cost grounds.

Particular attention was paid to studying the effectiveness of strips of sun grass and in trapping coarse sediment. In this regard, Astroturf mats were placed in front of, within and behind vegetated strips, the thickness of deposited sediment was measured and the size distribution of accumulated sediment was determined using an LS-coulter counter. This simple approach yielded some informative results, but the research design did not support measurement of velocities and turbulence in the flow approaching, within and behind the vegetation – data vital to explaining how the buffering worked in process terms. Also, no consideration could be given to the impact of buffer strips on local stage-discharge relationships (i.e. their effect in blocking the flow) or their wider impact on field-scale sedimentation patterns. Although the results are useful in supporting the case for considering wider employment of grass buffer strips, their explanatory and scientific utility is seriously limited by the simplicity of the research method.

An inventory of local farmers' vernacular knowledge concerning the physical and socio-economic factors affecting decision making on agricultural land use was compiled from the results of questionnaires, semi-structured interviews and focus group discussions. These techniques provided a good basis for this part of the study and were consistent with the 'farmer first' principle of applied agrarian research.

Integration of the influences of physical and socio-economic factors that affect the quality of land use decision making was achieved using a Bayesian Network (BN). This approach enables users make probabilistic inferences concerning land use suitability and the quality of decisions (good, OK, bad), which is entirely new to floodplain research in Bangladesh. This method proved to be highly informative and could be used widely in helping farmers with agricultural decision making all over the country.

The techniques used for data collection and analysis were effective, but I, like many other researchers in Bangladesh, experienced problems due to scarcity of and limited access to secondary data. For example, I used *mauza* (village) maps as base maps when collecting plot level land use information. However, the maps available in the public domain are very old (dating from the 1970s). Plot boundaries have been changed though time due to sharing land among siblings, while the boundaries of some plots could not identified at all due to river bank erosion. The quality and accuracy of the work would have been improved by access to modern maps and there seems no good reason why more up to date versions should not be made available to legitimate researchers at established universities nationally and internationally.

Finally, this research attempted to integrate physical and human processes operating on the floodplain based on the limited time and resources available for a doctoral study. This dictated that the floodplain be characterised using very basic parameters. Consequently, in the spatial and temporal contexts, this research covers only the active and young floodplain and two monsoon floods. Logistical issues were a continual problem, but I was fortunate in being able to mobilise a small team of individuals from my home university (Jahanganagar University) to assist me in this regard, greatly enhancing the volume and quality of the field data. I was also aided by the willingness of local, experienced farmers to share their knowledge. The point here is that the active cooperation and support of local academics and stakeholders is crucial to the viability and success of any study in a remote, agrarian society.

Finally, it is necessary to appraise the overall outcomes of this research in terms of the techniques, approaches and potential applications of the work. It is clear that Bangladeshi farmers use only their vernacular knowledge to account for sedimentation and socio-economic factors when making agricultural land use decisions, with only scientists using technological approaches to describe and define sedimentation and land suitability for agricultural crops. This research has shown that a Bayesian network could be helpful for farmers making local decisions and policymakers planning floodplain development that is adaptable and sustainable.

The Bayes approach could be implemented in two ways: first for motivation and awareness building from the bottom up through applications at the community level, with the help of village leaders and, second; through providing information and supporting education and dissemination from the top down through governmental bodies such as the SRDI and Bangladesh Department of Agriculture.

The research approach adopted here offers wide opportunities for the integration of physical and human influences on floodplain land use, which it would be possible to fit into floodplain research studies in similar environments in other parts of Bangladesh and other nations.

Finally, I would like to stress that main strength of this research stems from its use of primary data and information on sediment, flooding, vegetation and plot level land use collected at first hand and its use of vernacular knowledge gained through direct, formal and informal contacts with the farmers and other key stakeholders. I would also like to emphasise that its main limitations stem from the relatively short time available to perform the research coupled with the scarcity of logistic, technical and financial support available for a PhD study.

8.3 Recommendations for further work

This study represents an initial step towards establishing how sedimentation, vegetation and agricultural land use dynamics interact in the active and young floodplain of the Brahmaputra-Jamuna River in Bangladesh. The findings suggest that sedimentation has major impacts on the agricultural land use dynamics and that natural vegetation and agricultural crops significantly influence sediment movement and the way that deposition is distributed over the floodplain during an event. As the floodplain of the Brahmaputra-Jamuna is closely coupled to the main river and floodplain processes reflect a complex set of both physical and human controls, it has proven difficult to describe, integrate, analyse and interpret all of the relevant variables in a single study. In light of this, it is not surprising that the findings presented in this thesis highlight several areas that need to be pursued through further research and where more quantitative and collective work is required. In addition, while the study has answered the research questions posed at the outset, it has also raised a number of new questions which have not been fully answered and which would benefit from further work.

- **Further data collection**

Remote sensing (RS) techniques offer a wide range of object-based data at different spatial and temporal scales. It is now feasible to use high-resolution, RS data to monitor sedimentation, vegetation diversity and agricultural land use. Hence, it is recommended that the present study's data set could be extended and refined using RS data. In addition, at the regional scale land use evolution is slow, although short-term changes may occur during and after an unusual flood event in response to the deposition of thick and/or coarse sediments (as revealed in this research). It follows that long-term monitoring of floodplain land use based on RS data should be used to provide better information on floodplain land use and the environment. Notwithstanding the power of RS to cover large areas and timescales, ground trusting would still be necessary and data regarding the farmers' perception of the floodplain environment, rationale for agricultural crop selecting can only be collected through participatory approaches, and these must be continued.

- **Methodological issues**

This study has mainly used exploratory data analysis, based on mixed methods, interpolation through kriging in a Geographical Information System, and Bayesian Networks (BNs) and Influence Diagrams (IDs) as decision support tools. Application of BNs and IDs to floodplain research is new in Bangladesh and these are methods, which are not completely validated for this application. It is recommended that the utility and applicability of other, relevant modelling approaches in multivariate analysis (for example those available in SPSS), and other interpolation techniques (such as Cokring in the ARC GIS environment) should be investigated.

In addition, there is currently very little public participation in environmental assessment and decision-making in Bangladesh and addressing this problem would eventually lead to better decisions. While, the findings reported here are encouraging in terms of demonstrating the benefits of involving stakeholders in terms of improving our understanding of the floodplain environment, further work that addresses methodological issues is certainly necessary and, only after a programme of further research and development will the practical and theoretical validity of the current research be validated and fully established.

- **Broader findings**

Finally, this study has established the spatial and temporal distribution of sediment deposition thickness and grain size in the study area and assessed the effects of sedimentation on agricultural land use and land use change, based on observations made during on two floods (one abnormally high and the other normal). The results starkly illustrate the sensitivity of sedimentation and land use to variations in the magnitude and duration of flooding, which are climatically induced. The results have further demonstrated contrasts between the impacts of rain-fed and river water flooding on sedimentation and soil fertility. The balance between rain-fed and river flooding is dependent on short-term climatic variability its impact on agricultural cropping patterns is of particular public interest.

The implications of these findings are that further research effort is now essential in order to improve our understanding of the impacts of global and regional climate change on the floodplain environment in Bangladesh, considering both short-term fluctuations and longer-term, irreversible environmental change. In summary, it is now necessary to initiate new research investigating the impacts of regional climate change on flooding, sedimentation, vegetation and agricultural land use dynamics in the Brahmaputra-Jamuna floodplain, work that would form an extremely relevant extension of this thesis.

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APPENDIX –A

FACTS AND FINDINGS OF QUESTIONNAIRE SURVEY

Study Site: Jamuna Floodplain (Village: *Bara Bannia*, Thana / *Upazila:* Daulatpur, District: Manikganj, Bangladesh)

Section A: Demographic and socioeconomic aspects of the respondent

Name of the variables	Code	Description
1. Respondents' Age (*What is your age (years?)*)	1	≤30
	2	31- 40
	3	41-50
	4	51-60
	5	≥60
2. Respondents' profession (*What is your profession/job?*)	1	I farm my own land
	2	I employ other people to farm my land
	3	I rent my land out for others to farm
	4	I am cash crop farmer
	5	I am a tenant farmer who pays for land with money
	6	I am a tenant farmer who pays for land with crops
	7	I am a perennial farm worker/labourer
	8	I am a seasonal farm worker/labourer
	9	I am School teacher
	10	I am chairman/member/village leader of local administration (*Union Parisad*)
	11	I am local agricultural supervisor
	12	I am retired farmer (Due to elderly don't do agriculture)
3. Respondents' Education (*What is your level of education?*)	1	Illiterate
	2	I can only sign my name
	3	I am semi-literate (dropped at school)
	4	I have passed Secondary School Certificate (SSC)
	5	I have passed Higher Secondary Certificate (HSC)
	6	I have passed undergraduate
	7	I have passed postgraduate
4. Respondents' family size (*How many people in your house hold?*)	1	Small Family (≤4)
	2	Medium Family (5-7)
	3	Large Family (>7)

Name of the variables	Code	Description
5. Number of agricultural worker *(How many members of your family are involved in agricultural work?)*	1 2 3 4	≤2 3-4 ≥5 None
6. Farm size *(What is the total amount of land you own/ rent in hectares?)*	1 2 3	Small farm (<1hectare) Medium (1-2 hectare) Large farm (2 hectare)
7. Monthly expenditure *(What is your monthly expenditure in Taka?)*	1 2 3 4	High expenditure (>10,000 TK.) Medium expenditure (7000-10,000 TK.) Low expenditure (5000-7000 TK.) Very Low expenditure (<= 5000 TK.)
8. Source of Income *(What is your main source of income?)*	1 2	Agriculture Non-agriculture

Section B: Farmer's Knowledge on floodplain, flood, flooding and sedimentation

Name of the variables	Code	Description
9. Perceptions' about floodplain (*What do you understand by the term 'floodplain'?*)	1	The flood plain is a level land
	2	The floodplain is where siltation occurs by river water
	3	The floodplain is the area of land which is adjacent to the river
	4	The floodplain is the area of land which is periodically inundated
	5	I do not have any idea about this
10. Understanding flood and flooding (*What level of water would you consider a flood -Bonna or flooding-Barsha*)?	1	When crops fully submerged which is considered as flood
	2	When crops partially submerged which is considered as flooding
	3	When roads are inundated which is considered as flood
	4	When settlements are inundated which is consider as flood
	5	When the level of water hinders / hampers our daily life which is known as flood.
11. Consider the flood and flooding (*How do you consider flood (Bainnah) or flooding (Barsha) for agriculture?*)	1	Flooding is extremely good for agriculture
	2	Flood is not good for agriculture
12. Types of flooding (*How do you class the flooding?*)	1	Rain-fed flooding
	2	River water flooding
13. Preference of flooding (*What types of flooding do you prefer/ expect?*)	1	Rain-fed flooding
	2	River water flooding
14. Causes of prefer and non-preferring rain fed flooding (*Why do you consider Rain-fed flood to be suitable or unsuitable for agriculture?*)	1	It produces wash load from surrounding high land which increases soil fertility
	2	It damages less of crops
	3	It is good for standing crops
	4	Clear water is good for Photosynthesis synthesis by submerged vegetation, decomposed vegetation and increase soil fertility
	5	It produces Blue-Green Algae (BGA) which increases soil fertility
	6	It does not carry river sediment, so less suitable for agriculture

Name of the variables	Code	Description
15. Causes of prefer and non-preferring rain fed flooding (*Why do you consider Riverine flood suitable or unsuitable for agriculture?*)	1	It carries fine silt (*poli*) which increases land fertility
	2	If it is short duration flood then it can be damage the crops less
	3	If it is long duration flood then it can be damage the crops more
	4	It carries coarse sand which damages the crop
16. Sediment identification techniques (*How do you identify the sediment?*)	1	I look at / consider colour of the sediment (Dark grey colour sediment is silt dominant, which is highly suitable for agriculture; Blackish colour sediment is clay dominant, which moderately suitable for agriculture and whitish colour sediment is sand dominant, which is not suitable for agriculture.)
	2	I examine the texture of the sediment by hand (If the sediment is sticky then it is clay dominant and if is not sticky but smooth and fine grains are present then it is silt dominant and if it has coarse grains which can be wiped easily from the hand then the sediment is sand dominant)
	3	I base on a decision using my farming experience
	4	I seek advice from elderly people as well as local agricultural supervisor
	5	Tilling (high, moderate and low aggregation)
	6	Throw water on the soil (well, medium and poor infiltration)
	7	Feel the handful soil weight and wetness (low, optimum and high moisture)
17. Sediment identification techniques (*How do you identify the sediment?*)	8	Taste with tongue (Irritating condition)
	9	Visual perception of vegetation abundances
18. Soil typology and quality (*How many types of soil you familiar with and rank the quality?*)	1	*Bele maati* (Sandy soil), *Motamoti* (Medium)
	2	*Bele-doas maati* (sandy loam soil), *Bhalo* (Good)
	3	*Poli maati* (Silt soil), *Beshi Bhalo* (Better)
	4	*Poli doas maati* (Silt loam soil), *Sobcheye Bhalo* (Best)
	5	*Aintel maati* (Clay soil), *Khub mondho* (Very poor)
	6	*Aintel doas maati* (Clay loam soil), *Mondho* (Marginal to Poor)

Section C: Farmer's Knowledge on land types, cropping season and number of crop selection.

Name of the variables	Code	Description
19. Land typology by famers (*How do you class the lands?*)	1	*Vita, Dhaanga, taan* (High land*), normally above the flood level*
	2	*Chala, Kandi* (Medium high land 1*),* Crops inundated but not damaged
	3	*Chwak* (Medium high Land 2*),* Crops inundated and partially damaged
	4	*Naal* (Medium low land, Crops inundated and mostly damaged
	5	*Khal, Byde* (Low Land), Only dry season's crops available
	6	*Beel* (Very low land), Only dry season's crops available
	7	*Nodi* (Bottom land), Year round inundation
20. Crops Season typology (*How do you count crop seasoning*)	1	*Grismakal/ Prak-kharif* (Pre-monsoon; March-May, Hot-humid),Crops; Jute, rain fed *B. Aus* and *B. Aman* paddy
	2	*Barshakal /Kharif/ Bhadai (*Monsoon; June-September, Hot, humid, heavy rain), Crops: Transplanted, sown and HYV *Aman*
	3	*Hemantakal/ Aghnai / Haimantic (Post-monsoon; October-November, Hot, humid, but less rain), Crops: IRRI and Boro paddy, lentils and mustard*
	4	*Shithkal/ Rabi (Dry season; December-February, Dry, mild, Sunny), Crops: Oil seeds, wheat, peanuts, onion, sugarcane, winter vegetables*
21. Land Suitability for agriculture (*Which lands are suitable for agriculture?*)	1	*Nal* (suitable for agriculture)
	2	*Chala* (moderately suitable for agriculture)
	3	*Kanda* (not suitable for agriculture)
	4	*Ditch* (Seasonal water logged area unsuitable for agriculture)
	5	*Vete* (high land, suitable for settlement rather than agriculture)
	6	*Beel* (Low land which is perennial water logging area-suitable for *Boro* paddy)
22. Farming type (*What type of farming do you do?*)	1	Subsistence farming
	2	Cash crop farming
23. Types of crops (*What types of crops do you cultivate?*)	1	*Rabi* crops (Potato, pulses, mustard, wheat, maize, coriander and winter vegetables)
	2	*Kharif* crops (Jute, *aman* paddy and *aus* paddy, sesame, sugarcane and summer vegetables)

Name of the variables	Code	Description
24. Number of Crops *(How many crops do you cultivate on a piece of land each year and why?)*	1	Single crops (if is sand dominant soil and very low land)
	2	Double crops (if it is silt dominant soil, medium- high land but vulnerable to flood inundation)
	3	Triple crops (if it is silt dominant, most flood- free land in normal flood)
25. Sediment types and crops associations *(Which crops do you choose for particular sediment type?)*	1	Sand dominant sediment: mainly peanuts, sesame, & water melon.
	2	Silt dominant sediment: mainly *aman* and *aus* paddy, jute, sugarcane, potato, wheat & maize)
	3	Clay dominant sediment (mainly *boro* paddy and mustard)
26. Way of decision taking in land suitability for crops *(How do you make a decision whether this crop will be suitable or not for this land?)*	1	I base my own experience
	2	Following discussion with elderly people and local agricultural supervisor
	3	After considering market demand and price of goods
	4	After considering my family's food needs
27. Farming system *(Have you got any understanding of the term 'traditional' and 'modern' farming systems?)*	1	Yes, I have the idea from elderly and local agricultural supervisor
	2	No, I have not any idea about this
28. Practised farming system *(What farming systems do you practise?)*	1	Traditional farming system
	2	Modern farming system
29. Causes of practising traditional farming system *(Why do you practise Traditional farming system?)*	1	I learnt from elderly people and experienced in traditional farming systems
	2	Although it s time consuming but this system is less expensive than modern arming systems and we got enough labour to follow that.
	3	Very often we don't get proper supports for modern farming system
30. Causes of practising Modern farming system *(Why do you practise Modern farming system?)*	1	It is less time consuming to cultivate land than traditional farming system.
	2	Although it is expensive system but the yield is much greater
	3	I do have support for modern farming
31. Number of crops on natural levee *(How many crop do you produce on the natural levee / near the riverbank, and why?)*	1	Usually three crops if it not affected with severe flood and river bank erosion
	2	Depending the soil condition I do prefer 2 crops
	3	Single crops if it is sand dominant soil

Name of the variables	Code	Description
32. Number of crops on back slope and back swamp (*How many crops do you produce on land which further away from natural levee / riverbank, and why?*)	1	Just immediate after the natural levee (back slope) I do produce three crops in a year because it is mostly silt dominant soil
	2	If the land type is vulnerable to flood then I do prefer for double crops
	3	Particularly the back swamps zone , I do prefer single crops and sometime, but if the water is completely drying out from land , then I do cultivate double crops.
33. Land suitable for crops (*Which land is most suitable for crop production?*)	1	Near the River bank (Natural levee)
	2	Lands after the river bank (back slope)
	3	Further away from the river (Back swamp)
34. Principle criterion for number crop selection (*What principle criterion do you consider for crop selection on a piece of land?*)	1	We choice based on the needs of household (family size and food demand)
	2	We consider the plot size, because if the my plot size is small and the adjacent plot is large then we have to follow the larger plot's crop selection (farm or plot size)
	3	Crops market price
35. Family size and earning from lands (*What is your family size and how much do you earn from agriculture annually?*)	1	Small family: 80,000TK.
	2	Medium family : 100,000 TK.
	3	Large family : 150,000 TK.
36. Family size and expenditure (*What is your family size and expenditure annually?*)	1	Small family: 72,000TK.
	2	Medium family : 120,000 TK.
	3	Large family : 165,000 TK.
37. Support for agriculture (*What supports do you get from Government or Non-government sources for farming?*)	1	I get agricultural information from Governmental bodies
	2	I get monetary loan from the non-governmental bodies
	3	I do not get any supports
38. Share farmer crop selection decision (*If you are a share farmer, does the landowner influence your choice of crop?*)	1	Yes, landowner decides the crop
	2	No, I decide the crop grown

Section D: Farmer's perception about floodplain vegetation

Name of the variables	Code	Description
39. Vegetation types *(How do you class the vegetation according to land forms?)*	1	Tree spices around the homestead forest in high land zone
	2	Shrubs vegetation along the natural levee close to the river
	3	Shrubs and herbs in the back slope and back swamps
40. Vegetation traps the sediments *(Are you aware about the sediment trapping by vegetation, if so then why?)*	1	Yes, I know that Sun grass (*Kaisha* grass), Bushes, Floating vegetation (*Korcha* grass) and hydroponics
	2	Agricultural crops like standing crops *aman* paddy, jute, *sesbania* and sugarcane field also trap the sediment.
	3.	I don't have any idea about this
41. Consideration the vegetation in trapping sediment *(What vegetation do you keep in the field in trapping the sediment and why?)*	1	I do prefer to keep the land with *aman* paddy, because I need crops yield as well and deep water *aman* can sustain in the water moreover standing crops like jute, sugarcane *sesbania* also be considerable.
	2	I do not prefer the sun grass to keep as buffer strips because it is deep rotted and can hamper my next agricultural crops on yield
	3	I do count the all types of bushes as extra burden as weeds for crops
42. Threatened vegetation during flood *(During flood, what type of vegetation is threatened?)*	1	Tree species (Jackfruit, *Koroi, Bon Jika*)
	2	All types of vegetables
	3	Crops (*aus* paddy)
43. Blue Green Algae *(Are you aware of Blue Green Algae (BGA)?)*	1	Yes, I know which usually produce in the rain fed flooding area in the paddy field
	2	No, I do not have any idea about BGA.
44. Importance of BGA *(Do you think Blue Green Algae (BGA) is useful in soil fertility, and how?)*	1	Yes, I do think it is useful for soil fertility because it increases soil fertility after it is mixed with the soil following ploughing
	2	I do consider it as weeds and hence I remove away from field and it is harmful for paddy and decrease the crop's yield

APPENDIX- B

Land use survey index sheet; *Mouza*/Village: *Bara Bania*; *Upazila*: *Daulatpur*; District: *Manikganj*; Bangladesh

Plot No.	Land use															7. Land Type					8. Drainage System			9. Relief			10. Flooding		
	1	2			3			4				5		6															
		2a	2b	2c	3a	3b	3c	4a	4b	4c	4d	5a	5b	6a	6b	7a	7b	7c	7d	7e	8a	8b	8c	9a	9b	9c	10a	10b	10c

Index: Code used during field survey for land use plot level information:

1. **Settlement**

2. **Agricultural Land**
   2.a Single crop
   2.b Double crops
   2.c Triple crops

3. Vegetation
3.a Homestead Forest
3.b Shrubs
3.c Herbs

4. Water Bodies
4.a Ditch
4.b *Beel* (Back swamp)
4.c River
4.d *Khal* (intermittent channel)

5. Fallow Land
5.a Current Fallow
5.b Permanent Fallow

6. Govt. (*Khas*) Land
6.a Road
6.b *Hallot*

7. Land Type
7.a High Land
7.b Medium High Land
7.c Medium Low Land
7.d Low Land
7.e Very Low Land

8. Drainage System
8.a Good
8.b Ok
8.c Bad

9. Relief
9.a Plain Land
9.b Uneven Land
9.c Slope Land

10. Flooding
10.a Perennial
10.b Seasonal
10.c Not Flooded

APPENDIX –C

Calculation of Margin of error, confidence interval and the sample size

Respondent types	Total population in each (x)	Deviation about the mean $(x-\bar{x})$	$(x-\bar{x})^2$
Farm own land	173	127.66	16298.78
Employ people to farm land	49	3.66	13.44
Rent land out to farm	82	36.66	1344.44
Cash crop farmer	27	-18.33	336.11
Tenant farmer pays money for land	11	-34.34	1178.78
Tenant farmer pays crops for land	44	-1.33	1.78
Perennial farm worker	38	-7.33	53.78
Seasonal farm worker	38	-7.33	53.78
School teacher	16	-29.33	860.44
Chairman/members	22	-23.33	544.44
Local agricultural supervisor	11	-34.33	1178.78
Retired farmer (Due to elderly)	33	-12.33	152.11
SUM	544	0	22017
Count	12	12	12
Mean	45.33		
Variance(σ^2)	2001.52		
Standard Deviation (σ)	44.74		
Significance level (Z 95%)	1.96		
Standard Error	4.47		
Margin of Error (E)	8.78		

Sample size (n)= $\left(\frac{Z_{\frac{\alpha}{2}}\sigma}{E}\right)^2 = \left(\frac{1.96\times 44.74}{8.78}\right)^2 = 99.75 = 100$

Where, $Z_{\frac{\alpha}{2}}$ = Significance level (95%)= 1.96, [α=1-.95=0.05, α/2=0.05/2=0.025, $Z_{0.25}$ =1.96]

Standard Deviation (σ) = 44.74

Margin of Error (E) = How far off the estimate is likely to be=8.78

Confidence Interval (CI)= $\bar{x} \pm E$ = 45.33± 8.78= 36.55-54.11=37%-55%

APPENDIX –D

The vegetation abundances calculation procedures

The absolute frequency, relative frequency, density, relative density and abundance of vegetation in each quadrat were calculated by using following equations:

$$d = \frac{x}{A} \quad \text{..........................(1)}$$

$$rd = \frac{x}{N} \times 100 \quad \text{..........................(2)}$$

$$f = \frac{n}{A} \times 100 \quad \text{..........................(3)}$$

$$Rf = \frac{f^i}{\sum f^i} \times 100 \quad \text{..........................(4)}$$

$$a = \frac{x}{n} \quad \text{..........................(5)}$$

Where, d =Density of species per unit area; rd = Relative density; x = Total number of individual of each species; n = No. of Quadrate Occurrence; N = Total number of individual all species; A = Total number of quadrats sampled; Rf = Relative frequency; f^i = Frequency of the species in stand, and; $\sum f^i$ = Sum of the frequencies for all species in stand.