Brandenburg University of Technology at Cottbus
Faculty of Environmental Sciences and Process Engineering
Department of Ecosystems and Environmental Informatics
International Study Course Environmental and Resource Management

Brandenburgische Technische Universität Cottbus

Title of the PhD Thesis

Cultural Landscape Changing due to Anthropogenic Influences on Surface Water and Threats to Mangrove Wetland Ecosystems: A Case Study on the Sundarbans, Bangladesh

A thesis approved by the Faculty of Environmental Sciences and Process Engineering at the Brandenburg University of Technology at Cottbus in partial fulfillment of the requirement for the award of the academic degree of Doctor of Philosophy (Ph.D.) in Environmental and Resource Management.

By

B.Sc. (Honours), M.Sc., M.A.

Md. Shafi Noor Islam

From Jamalpur, Bangladesh

Supervisor : Professor Dr. rer. nat. habil. Albrecht Gnauck
Supervisor : Professor Dr. rer. nat. habil. Hans-Jürgen Voigt

Date of the oral examination: 25th June 2008

Brandenburgische Technische Universität Cottbus
Fakultät für Umweltwissenschaften und Verfahrenstechnik
Lehrstuhl für Ökosysteme und Umweltinformatik
Internationale Studiengang Umwelt-und Ressourcen Management

Brandenburgische Technische Universität Cottbus

Titel der Dissertation

Veränderung einer Kulturlandschaft infolge anthropogener Einflüsse auf Oberflächengewässer und Bedrohung von Mangrovenökosystemen am Beispiel der Sundarbans, Bangladesch

Von der Fakultät für Umweltwissenschaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus zur Erlangung des akademischen Grades eines Doktor of Philosophy (Ph.D.) genehmigte Dissertation.

Von

B.Sc. (Honours), M.Sc., M.A.

Md. Shafi Noor Islam

Aus Jamalpur, Bangladesch

Gutachter : Professor Dr. rer. nat. habil. Albrecht Gnauck
Gutachter : Professor Dr. rer. nat. habil. Hans-Jürgen Voigt

Tag der mündlichen Prüfung : 25th June 2008

Brandenburg University of Technology at Cottbus
Faculty of Environmental Sciences and Process Engineering
Department of Ecosystems and Environmental Informatics
International Study Course Environmental and Resource Management

Brandenburgische Technische Universität Cottbus

Declaration

I, Shafi Noor Islam, hereby declare that this thesis has been written independently. It has not been published anywhere before. Where materials of other authors were used as, due reference and acknowledgement has been stated properly.

....
Md. Shafi Noor Islam

Cottbus, 30th November 2007

Acknowledgements

A Doctorate research endeavour is always accomplished with the assistance of many experts, so any attempt to acknowledge them by name who rendered services is impossible and for this I am sorry and ask for their understanding. It is my ardent task to record my debt to my supervisors Professor Dr. rer. nat. habil. Albrecht Gnauck, Chair of Ecosystems and Environmental Informatics and Professor Dr. rer. nat. habil. Hans-Jürgen Voigt, Chair of Environmental Geology, Brandenburg University of Technology at Cottbus, Germany. I must acknowledge in stimulating my ideas in different ways and remain obliged for the energetic care with which they have gone over the manuscript of my research and for improving and clarifying the exposition of the statements.

I got background information from; Mangrove Ecosystems, Functions and Management by Lacerda, L.D.D, Springer Verlag, Berlin. The Mangrove of Sundarbans, Volume Two: Bangladesh by Zakir Hossain and Gaytri Acharia, IUCN, Bangkok. Mangrove Forestry in Bangladesh by Siddiqi, N.A, University of Chittagong, Surface Water Modelling of Sundarbans Biodiversity Conservation Project Report 2003 supplied by IWM-Dhaka, with important technical-hydrological terms, informations, definitions and data to these books which I used very openly in my dissertation, I acknowledge my debt. Beside these Soil Resource Development Institute-SRDI, Bangladesh Centre for Advance Studies, CEGIS-Dhaka, Forest Department, Department of Environment and Forestry, Centre for Integrated Rural Development Programme for Asia and the Pacific-CIRDAP, Rupantar, CDS, BARCIK the national NGOs in Bangladesh they supplied me a lot of information and reference reports.

I am grateful to Professor Dr. Maudood Elahi, Professor Mesbah-Us-Saleheen, Department of Geography and Environment, Jahangirnagar University, Dhaka. Professor Dr.A.H.M.A. Baqee University of Dhaka, Professor Dr.A.K.M. Kalam University of Waterloo Canada, Dr. Nieaz Ahmed Siddiqi and Dr. Luthfe Alam of Bangladesh Forest Research Institute Chittagong, Amirul Islam and Abdur Rahman of Institute of Water Modelling (IWM) Dhaka, Dr. Hero Heering Consultant of IPAWAM Bangladesh, Dr. Beth Middleton, Secretary General of Society of Wetlands Scientists, USGS, USA.

I acknowledge the assistance of the professors and staff of BTU Cottbus, Germany especially to Professor Dr. Michael Schmidt-Head of ERM- PhD programme, Professor Dr. Gerhard Wiegleb and Professor Dr. Marie-Theres Albert of World Heritage Studies, Ms. Kathryn Prouty M.A, Beata Körner M.A, and Dipl.-Ing. R. Schuhr of International Office, Dipl.-Geogr. Ralph Heinrich, Dipl.-Ing. Harmut Nemitz and Katya Rösch, Dept. of Ecosystems and Environmental Informatics, Bernadett Hoppe Co-ordinator of ERM PhD programme and my colleagues and friends specially Jean Duclos Alegue Feugo (Cameroon), Irene Sachs, Nicole Link(Germany), Raynah Burke (Panama), Wie Shouke (China), Delphine Oliver, Anne Bousquet (France), Iana Debora (Brazil), Alena Kiptsevich (Belarus), Agnieszka Bukowska, Agnieszka Plwowarczyk, Aneta Grabanska, Marta Janeczko, Magdalina Pybaczewska, Margaret Frackowiak (Poland), Pierre Burtin (Sweden), Virginia Appendino (Argentina), Tijani, Frank, Seth, Francis, Effah (Ghana), Masgidi (UAE), Badre Ichrak (Morocco), Collins (Nigeria) and Engel Berth Soto (Mexico). My sincere thanks to Bangladeshi students in Germany like Rumana, Sharif, Lipon and others from different parts in Europe, USA and Canada those always encouraged me to finish my Doctorate dissertation in time.

I am very grateful to my mother, brothers, sisters and relatives for their constant support and encouragement during my studies and research at Brandenburg University of Technology at Cottbus, Germany.

Md. Shafi Noor Islam 30th November '07 Cottbus, Germany

Table of Contents

Chapter 3 The Sundarbans Study Area 36

Chapter 4 Modelling of Water Salinity 78

Abstract

Cultural landscapes are areas of exceptional beauty, containing superlative natural phenomena and are of ecological importance. At present cultural landscapes and wetlands are the most spectacular global issues for economic growth and balancing of ecosystems. The Sundarbans has an outstanding universal value where the cultural landscape was shared by the indigenous pastoral society over thousand years ago and it is still visible. The site is representing significant ongoing ecological and biological processes in the evolution and development of mangrove ecosystems and communities of plants and animals. It is situated in the Ganges transboundary catchment which is known as the single largest stretch of productive mangrove ecosystems in the world. It covers 10,000 km^2 between Bangladesh and India. The Sundarbans portion of Bangladesh is about 62 % and covers an area of 6017 km^2. It was declared as world natural heritage site by the UNESCO in 1997 and as a Ramsar site in 1992 already.

There is an agglomeration of biodiversity with 66 different species of mangroves growing there. For comparison: 70 species of mangroves are found in the world. A large part of mangrove wetlands in Bangladesh, almost 45 %, have disappeared within the last three decades. The Gorai River is the main tributary of the Ganges which supplies downstream freshwater to the Sundarbans and ensures the ecosystems balance in the coastal region. Since the diversion of the Ganges water at Farakka Barrage in India from early 1975, the salinity level has increased drastically in the south western part of the region. Due to the reduction of the Ganges flows the industries are facing serious problems. Inequality control of the products and fragile affects are demonstrating on agriculture, fisheries, navigation, and hydromorphology, quality of drinking water and mangrove wetlands ecosystems. As a result, about 170,000 hectares (20.4%) of new land has been affected by various degrees of salinity during the last three decades. 38 % of the country's territory and 33 % of its population is already affected by salinity intrusions.

The saline front defined by the 0.5 dS/m isohaline has penetrated in the Nabaganga River as far north as Magura is far from the coast (240 km). Similarly about 6 dS/m has penetrated 173 km from the Sea in the Atharobanka River to the vicinity of the off-take from the Madhumati River. The research findings are showing 10805-21610 dS/m salinity is the best productive range in Sundarbans, where only 20 % of the area is within 32415 dS/m range of salinity and 80 % of the area (4813.60 km^2) has a salinity rate over 32414 dS/m. The dominant species *Heritiera fomes* and *Ceriops decendra* are affected by top-dying disease which is recognised as key management concern. Procedures of water salinity modelling of 13 rivers in the Sundarbans region lay out increasing salinity trends.

Fourier Polynomial Models have been done on 13 rivers where the time series approach (4 years) has been considered. The results show that only one river has crossed the salinity threshold line of 20 ppt or 43,220 dS/m which was the maximum value in 2000. Whereas 6 rivers have crossed in 2001, 8 rivers have crossed in 2002 and important 11 rivers have crossed the water salinity threshold line in 2003. According to average peak values of river water salinity there are 4 rivers (basin 1, 2, 3 and 4) that are in good condition, two rivers (basin 7 and 9) carry the moderate situation and 7 rivers (basin 5, 6, 7, 8, 10, 12 and 13) carry the high salinity rate in the dry season, which are major threats for mangrove ecosystems in the Sundarbans. The high salinity zone is located in the south-western corner of the Sundarbans; the previous values were 38,898-54,025 dS/m while the present values are 54,025 – 69,152 dS/m. Furthermore the area has been extended from South to North and East to West direction. The Fourier Polynomial models show the cyclic increasing behaviour of water salinity in the Sundarbans Rivers.

Considering the results of all models and threshold values of water salinity for the Sundarbans case, it is clearly indicated and forecasted the message that upstream fresh water supply is necessary and emergent for the protection of cultural landscapes and mangrove wetlands ecosystems in the Sundarbans region. As priority is given by surface water salinity modelling, statements are formulated to support planning activities and to protect a special natural heritage site. The findings of this study would be a potential contribution to make a comprehensive management plan for the long-term conservation and protection of the cultural landscape and mangrove wetlands ecosystem in the Sundarbans region.

Zusammenfassung

Kulturlandschaften sind oft Gebiete von außergewöhnlicher Schönheit, die sowohl natürliche Phänomene repräsentieren, als auch von ökologischer Bedeutung sind. Kulturlandschaften und insbesondere Feuchtgebiete zählen zu den wichtigsten globalen Kernpunkten für Wirtschaftswachstum und für das Gleichgewicht von Ökosystemen. Das Ökosystem der Sundarbans hat einen überragenden universellen Wert. Bereits vor über tausend Jahren wurde diese Kulturlandschaft von der einheimischen Landbevölkerung genutzt. Dies ist auch heute noch sichtbar. Am Ökosystem der Sundarbans lassen sich die biologischen Prozesse und die ökologische Entwicklung der Mangrovenökosystem und der Lebensräume von Pflanzen und Tieren erkennen. Die Sundarbans liegen im Einzugsgebiet des die nationalen Grenzen überschreitenden Ganges. Sie sind weltweit bekannt als größtes und ergiebiges Mangrovenökosystem. Das Mangrovenökosystem umfasst eine Fläche von 10.000 km² zwischen Bangladesch und Indien. Der Anteil von Bangladesh an den Sundarbans beträgt 62% und umfasst ein Gebiet von 6017 km². Im Jahr 1997 wurde es von der UNESCO zum Weltnaturerbe erklärt und gemäß der Ramsar-Konvention als Ramsar-Feuchtgebiet im Jahr 1992. Das Gebiet schließt eine Artenvielfalt mit 66 Mangrovenarten ein. Zum Vergleich: Es gibt bislang 70 bekannte Mangrovenarten auf der Erde. Ein sehr großer Teil, fast 45 % der Mangrovenfeuchtgebiete von Bangladesch, sind in den letzten drei Dekaden verschwunden.

Der Gorai-Fluß ist der Hauptarm des Ganges, der die Sundarbans stromabwärts mit Frischwasser versorgt und das Gleichgewicht des Ökosystems in der Küstenregion gewährleistet. Seit Anfang des Jahres 1975 wird der Ganges im Farakka Stauwehr (Indien) umgeleitet. Seitdem ist der Salzgehalt im westlichen Teil der Region drastisch gestiegen. Durch die Verringerung des Flussbetts des Ganges steht die Industrie vor ernsthaften Problemen bezüglich der Qualitätskontrolle der Produkte. Auswirkungen sind auch für die Landwirtschaft, die Fischerei, den Schiffsverkehr, die Hydromorphologie, die Qualität des Trinkwassers und die Ökosysteme der Feuchtgebiete der Mangrovenwälder zu verzeichnen. Durch die Versalzung sind bereits ca. 170,000 Hektar (20.4%) Neuland während der letzten drei Dekaden betroffen. Das entspricht 38 % des Hoheitsgebiets von Bangladesch. Die Versalzung hat sich bereits auf 33% der Bevölkerung ausgewirkt. Die Salzfront, die durch die 0.5 dS/m Isohaline definiert wird, ist bereits in den Nabaganga Fluss bis zur Stadt Magura, die 240 km von der Küste entfernt ist, eingedrungen. Im Atharobanka Fluss, der 173 Kilometer vom Meer entfernt ist, wird nahe des Abzweiges des Madhumati Rivers ein Salzgehalt von ca. 6 dS/m gemessen. Die Untersuchungsergebnisse zeigen, dass das Ökosystem der Sunderbans einen mittleren Salzgehalt von 10805-21610 dS/m aufweist, wobei 20 % des Gebietes einen Salzgehalt von 32415 dS/m und 80 % des Gebiets (4814 km²) einen Salzgehalt über 32414 dS/m aufweisen. Die dominierenden Arten Heritiera fomes und Ceriops decendra sind davon intensiv betroffen. Dies gilt als auffälligstes Ereignis in den Sundarbans. Die Modelle für den Salzgehalt von 13 Flüssen in der Region der Sundarbans zeigen steigende Tendenzen des Salzgehaltes.

Die Ergebnisse der Fourier-Modelle zeigen, dass nur ein Fluss den Grenzbereich des Salzwassergehaltes (20 ppt oder 43,220 dS/m) im Jahr 2000 übersteigt. Dagegen überschreiten bereits im Jahr 2001 6 Fließgewässer, im Jahr 2002 8 Fließgewässer und im Jahr 2003 11 Fließgewässer den Grenzwert des Salzgehalts. Entsprechend den mittleren Höchstwerten des Salzgehaltes sind 4 Fließgewässer (Bassin 1, 2, 3 und 4) in gutem Zustand, 2 Fließgewässer (Bassin 7 und 9) im mittleren und 7 Fließgewässer (Bassin 5, 6, 7, 8, 10, 12 und 13) im schlechten Zustand während der trockenen Jahreszeit. Dies ist eine der Hauptbedrohungen für die Ökosysteme der Mangrovenwälder in den Sundarbans. Die Zone mit dem hohen Salzgehalt liegt im südwestlichen Teil der Sundarbans. Lagen die Werte früher bei 38898-54025 dS/m, so sind es aktuell Werte von 54025 - 69152 dS/m, des Weiteren hat sich das Gebiet von Süden nach Norden und von Osten nach Westen vergrößert. Die Fourier-Modelle zeigen eine kreisförmige Zunahme des Salzgehaltes in den Flüssen der Sundarbans.

Fasst man die Ergebnisse der Dissertation zusammen, so lässt sich folgendes feststellen:

1. Es ist eindeutig zu erkennen, dass die Süßwasserversorgung lebenswichtig für den Schutz der Kulturlandschaft und des Ökosystems der Sundarbans ist.
2. Zur Vorhersage der Entwicklung der Sunderbans hat die Modellierung der Wassergüte, insbesondere des Salzgehaltes, höchste Priorität.
3. Administrative Anweisungen zum Schutz dieses Weltkulturerbes sind auszuarbeiten.
4. Die Erkenntnisse dieser Forschungsarbeit tragen dazu bei, einen langfristigen Managementplan für die Erhaltung und den Schutz der Kulturlandschaften und des Ökosystems der Sundarbans zu erstellen.

List of Figures

List of Tables

List of Abbreviations and Units

ACF – Additional Conservator of Forest

ADB – Asian Development Bank

ADFO – Additional Divisional Forest Officer

ADP – Annual Development Plan

AWB – Asian Wetlands Bureau

BARC – Bangladesh Agricultural Research Council

BBS – Bangladesh Bureau of Statistics

BIDS – Bangladesh Institute of Development Studies

BFRI – Bangladesh Forest Research Institute

BIWTA – Bangladesh Inland Water Transport Authority

BWDA – Bangladesh Water Development Authority

BWPAA – Bangladesh Wildlife Preservation Amendment Act

CARMDMA – Coastal Area Resource Development and Management

CCF – Chief Conservator of Forest

CEGIS – Centre of Environmental Geographical Information Systems

CF – Conservator of Forest

CITES – The Convention of International Trade in Endangered Species

DCCF – Deputy Chief Conservator of Forest

DFO – Divisional Forest Officer

DMA – Damaged Mangrove Areas

DoF – Department of Forest

EGIS – Environmental Geographical Information System

EORC – Earth Observation Research and Application Centre

EQS – Environmental Quality Standard

ESP – Exchangeable Sodium Percentage

FAP – Flood Action Plan

FEMAT – Forest Ecosystems Assessment Management Team

FRMP – Forest Resources Management Project

GBM – Ganges, Brahmaputra and Meghna Basin

GEF – The Global Environment Facility

IBP – International Biological Programme

ICOMOS – International Council on Monuments and Sites

IUCN – International Union for the Conservation of Nature

IWM – Institute of Water Modelling

MAB – Man and Biosphere

MAF – Million Acre Feet

MCPFE – Ministerial Conference on the Protection of Forest in Europe

MCR – Mangrove Conservation Reserve

MFR – Mangrove Fisheries Reserve

MFR – Mangrove Forest Reserve

MoEF – Ministry of Environment and Forestry

MPO – Master Plan Organisation

NGO – Non Governmental Organisation

ODA – Overseas Development Authority

PRA – Participatory Rural Appraisal

RMSE – Root Mean Square Error

SAR – Sodium Absorption Ratio

SBCP – Sundarbans Biodiversity Conservation Project

SLR – Sea Level Rise

SPARRSO – Space and Remote Sensing Organisation

SRDI – Soil Resource and Development Institute

SSE – Some Squared Error

UNCED – United Nations Conference on Environment and Development

UNDP – United Nations Development Programme

UNECE – United Nations Economic Commission for Europe

UNEP – United Nations Environmental Programme

UNESCAP – United Nations Economic and Social Council for Asia and the Pacific

UNIPCC – United Nations Intergovernmental Panel on Climate Change

USGS – United States Geological Survey

WHC – World Heritage Convention

dS/m – deci Siemens per metre

ppm – Parts per million

ppt – Parts per thousand

1 ppt = 2161 dS/m (for NaCl)

1000 ppm = 1 dS/m

640 ppm = 1 ppt

1 dS/m = 1000 EC (µS/cm)

1 dS/m = 1 milli Siemens per centimetre (mS/cm)

EC_w dS/m – Electrical Conductivity of Water dS/m

EC_s dS/m – Electrical Conductivity of Soil dS/m

100 hectares = 1 km^2

Chapter 1
Introduction

1.1 General Background

In the analysis of cultures there are a number of threats in current conceptualisations of landscapes. The properties of cultural landscapes are linked to and represented by human observation and realisation. At present cultural landscapes are the most spectacular global issue for economic growth and balanced ecosystems. On the other hand water is a fundamental issue needed for human survival and their cultural development. There is an inter-linkage between cultural landscape development and water availability. Water is a critical resource for life and essential for economic success and sound ecosystems in an environmentally friendly society. Of the world's water about 97.5 % exists as saline water in the oceans and seas. Only 2.5 % exists as fresh water and 99 % of this is trapped in glaciers and ice caps. Water is required for domestic consumption, sanitary use, industrial use, hydroelectric power generation, agriculture, irrigation and protection of the ecology and ecosystems (Gleick, 1998). Presently more than 31 countries around the world, representing 8 % of the world population are facing chronic fresh water shortage (Biswas et al., 2000). Water related ecosystems, such as mangrove wetlands, meadows, marshlands are playing an important role in water resources management and drinking water supply in the community. But almost half of the world's wetlands have been destroyed in the past 100 years (Barbier, 1993). It has been estimated that 60 % of wetlands have been lost in America alone (Jenderedjiar, 2004). Mangrove swamps are some of the richest and most productive areas for the food chain in the sea and coastal water (Dickinson and Murphy, 1998). The floral elements in mangrove wetlands forests are responsible for primary productivity in phytoplankton and marine algae while those responsible for secondary and tertiary productivity are zooplankton and benthic animals respectively (Parikh and Datye, 2003). Considering all the elements of mangrove wetlands, the Sundarbans which stands over the Ganges basin is playing an incomparable role in balancing and protecting the coastal wetland ecosystems in the Bengal basin (Banerji, 1981; Islam, 2001). The coastal deltaic zone, an area of transition, is an ecotone between air, land and sea, and between terrestrial fresh water and marine saline water (Das, 1989). The three major rivers namely the Ganges, the Brahmaputra and the Meghna (GBM river systems) account for 85 % of the total dry season flow passing through the coastal zone of Bangladesh. In the Sundarbans there are rivers, streams, channels, canals and creeks which together number around 430. The names of the major rivers are included in the appendix (Appendix 5) and play an influential role in the economy and environment. The Ganges deltaic morphology of the south western region of Bangladesh is characterised by its funnel shaped vast network of rivers, strong tidal and wind action and enormous river discharge laden with bed, and suspended sediments. The hydro-geomorphology of the region has very active dynamics and complex nature (Mafizuddin, 1993). The Sundarbans mangrove forest is situated in the Ganges river catchment area in Bangladesh. The southern part (1,400 km²) of the Sundarbans has been declared by the UNESCO as a natural world heritage site in 1997. The Sundarbans were declared as the world's 560th Ramsar site wetlands in 1992 (Figure3.2) and includes the following wetland types: F (Estuarine Wetlands), G (Intertidal mud and, sand, or salt flats), I (Intertidal forested wetlands), and M (permanent rivers/ streams /creeks). The international importance and inclusion of the Sundarbans as a Ramsar Wetlands site was based on Ramsar wetlands selection criteria 1c, 2a, 2b, 2c, 3b, and 4b. It provides habitats and nurseries to numerous wildlife and fishery resources (Holmgren, 1994). It stated in a FAO report (1995) that the Sundarbans is the first mangrove wetlands forest in the world which was brought under scientific management in 1892 (Rahman, 1995). In spite of the well-meaning sustainable management practices, a sign of anthropogenic stress is evident in the forest, such as substantial use of forest resources, damage of forest products and rapid expansion of shrimp cultivation around the forest; people have largely contributed to severe depletion of the forest resources. Biotic and abiotic factors have further exacerbated the hostile ecological and environmental damage (Holmgren, 1994).

The Sundarbans Ramsar site is part of the Ganges delta, including extensive productive mangrove forests and major river deltas flowing into the Bay of Bengal. The tidal management swamp is inundated twice daily. The depth and duration of tidal inundation depend on many factors like distance from the main rivers the sea including local relief and sediment load in the inundating water (Rahman, 1995; SBCP, 1997; Rahman and Chowdhury, 2001). The Sundarbans mangrove wetlands hold two world records. It is the world's largest expanse of mangroves and the world's largest tiger reserve. The cultural landscapes of Sundarbans receive frequent international attention after being afflicted by natural disasters such as massive flooding, tidal storm and surges and its vulnerable environmental ecological issues such as saline water intrusion in the Sundarbans areas, rapid siltation of major river's beds, and river bank erosion (Islam, 2001). Bangladesh is known as "land of water" or better "water in land" (Novak, 2001) is now facing acute water shortage during the dry season. The Ganges provides fresh drinking water, productive agriculture, industrial activity, forestry, fisheries, and navigation, prevents salinity penetration from the Bay of Bangal and above all, maintains the ecological balance of the country. The livelihood and ecology in the Ganges catchment of Bangladesh portion depends on the Ganges fresh water supply which is now under threat (Hasna et al., 1995).

Mangrove wetlands and their elements are a gift of nature. Natural beauty and the universal value of the wetlands property give us natural heritage. It is important for its floristic composition, economic uses and a wildlife habitat that has created for it a unique position not only in mangrove forestry but also in terms of cultural landscapes, culture and heritage. Natural resources have created culture and civilisation for human beings (Chapman, 1975; Drengsen and Taylor, 1997). At the same time human influence on nature, and on the planet, is indelible. In the case of the Sundarbans "Ganges water withdrawal during the dry season is one of the most critical environmental problems in Bangladesh, and while water loss is a concern for human beings, its ecological impact has never been assessed, an ecological damage since the construction of Farakka Barrage in 1975 will take decades to recover even if we get water now" (Hasna et al., 1998). In recent years with reduced freshwater discharge at the Farakka Barrage on the Ganges, more areas have been affected by stream flow salinity. Increasing water salinity is one of the significant and widespread forms of surface and ground water pollution, which are primarily effects of upstream freshwater withdrawal and salt intrusion in the coastal areas (Perry and Vanderklein, 1992; Nishat, 1993). The Gorai-Madhumati basin is directly affected by withdrawal of water from the Ganges. It was observed that substantial changes in the Ganges River flow generated effects on the Gorai River and the area depended on it. In the dry season, reduces flow in the Gorai River exacerbated problems of salinity in the Sundarbans region (Mirza, 1998). Increase in salinity, adversely affected agriculture, forestry, industrial production, and quality of drinking water and mangrove ecosystems (Khan, 1993). The River Balaswar in the east is the main source of fresh water although several others also bring water from the Ganges during the rainy season. These rivers are therefore, more susceptible to dry season reduction in stream flow and tidal intrusion of saltwater (Das, 2000; Hasan et al., 2001). Anthropogenic disturbances of nature have transformed natural landscapes through the process of fire, hunting, agriculture, climate change and industrial pollution. Some natural areas or sites have natural, cultural and economical values. These are important resources and heritage of the world communities and it is the responsibility of the world community to protect these invaluable natural resources and ecosystems.

1.2 Problems identification and data materials

The surface water flow in the rivers of the Sundarbans area mainly comes from the Ganges at the off-take of Gorai-Madhumati and from the lower Meghna through Swarupkati Kocha River. Salinity is the amount of dissolved salts present in river. It reflects the dominant forcing functions of freshwater discharge and oceanic exchange. Salinity content of river in the Sundarbans shows a special variability (Karim, 1988; Dewan, 1998; Ahsan and Biswas, 2001). Water salinity increase acts as a barrier to the natural growth of the plants and animals of the Sundarbans. Salinity posses physiological limit on the growth, survival and regeneration of mangroves plants. A general decline of the physiognomic structure of the forest is due to restricted growth of trees, which is related to salinity in soil and river water. If the present trend of salinity increase continues, some important trees like Sundari (*Heritiera fomes)* and Goran *(Ceriops decandra)* might vanish within 47 years (Iftekher and Islam, 2002). Moreover, some animals might not be able to adapt to the increasing trend of the water salinity in the region (Blasco, 1975). Salinity increases can cause changes in landscapes pattern of the areas adjoining the Sundarbans. Such land was previously used for crop production, and is now being converted to shrimp cultivation. Increasing salinity in the Sundarbans can hamper safe drinking water supply in Khulna city (Khan, 1993; Ahsan and Biswas, 2001). The scarcity of safe drinking water can force some people to drink unclean water which might cause some water bone diseases like cholera and diarrhoea (FAP, 1993). The water and soil salinity in the Sundarbans mangrove forest is rising. This trend is a serious threat to the ecological balance of the Sundarbans and cultural landscapes protection. For future generation benefits, proper management planning and controlling measures should be undertaken beforehand to maintain the water and soil salinity in the Sundarbans heritage site within an acceptable level. About 170,000 hectares or 1700 km² (20.4 %) new land has been affected by various degrees of salinity during the last three decades. The water management problem in Bangladesh is a complex phenomenon. Water resources in Bangladesh consist of three main components: rainfall, stream flows and groundwater storage. These components are closely interrelated. The main problems are centred on two issues a) The need for a mechanism that will optimally meet competing demands during the dry season, and b) planning and implementation of appropriate drainage and flood control measures during the wet season. In addition, adequate water management must also be predicated on the maintenance of water quality (Quazi et al., 1992). The surface water flow of the major source, the Ganges is reduced in Bangladesh due to upstream water diversions. Multiple factors are involved in compounding the issue of reduced river flow. Reduced flow of water in major rivers during the dry season has increased salinity encroachment in coastal areas, by reducing the fresh water pressure that normally counteracts the landward migration of salt water into underground aquifers. Indeed, aquifer salinity in the south-western region including the Sundarbans has increased significantly during the dry season in recent years. About 38 % of the country's territory and 33 % of its population is already affected by salinity in the water supply. The mangrove resources are generally considered as open access resources. Existence of species has social and ecological value: hence there is a need for their preservation. The goal of this research is the contribution of a comprehensive management plan for the long-term conservation and protection of the cultural landscapes and mangrove wetlands ecosystems in the Sundarbans. The results of water salinity modelling of the Sundarbans rivers will support planning by decision makers to protect the especial natural heritage site and mangrove wetlands ecosystems in the Sundarbans region in Bangladesh. The study was conducted at the field level and saline water and soil samples were collected for laboratory test for analysing the salinity situation and ecological and ecosystems degradation in the whole Sundarbans area. The study also involved discussions and interviews with the stakeholders, tourists and tour operators, shrimp cultivators, farmers, fishermen, shrimp collectors, business groups, local people, NGO leaders and decision makers and planners in the Sundarbans region. More than 3 months were spent in the Sundarbans in different sensitive areas where the ecosystems are under pressure and threatened due to human influences on surface water and environmental degradation. Areas and important locations include Munchiganj, Mirgang, Koira, Kasiabad, Mongla, Kathka, Kochikhali, Hironpoint, Dublar Char, Mundarbaria, Burigoalini and Saronkhola were covered during the survey and data collection in the Sundarbans. Primary data for surface water salinity were obtained from samples which had been collected from the 13 rivers of the Sundarbans by the Institute of Water Modelling (IWM) and BIWTA. This raw data was made available with the permission of the Asian Development Bank (ADB). The collected data has been used for water salinity modelling of the rivers in the Sundarbans. To understand the present ecological situation, other ongoing research activities and human influences which are harmful to the mangrove wetland ecosystems and what is relevant for data collection, a reconnaissance survey was conducted. As part of this survey the Ministry of Environment and Forest, Department of Forest, Sundarbans Bio-diversity Conservation Project (SBCP), Bangladesh *Parjaton* Corporation, tour operating organisations and other relevant environmental research organisations and different libraries in Dhaka, Chittagong, Rajshahi and Khulna cities were contacted. This survey helped to realise the present situation and provided the preliminary data on the existing environmental condition of the area to assist further research and development.

This study is an interdisciplinary environmental and natural resource management related research so I had to collect data and information based on interdisciplinary approach. The aim of this study is to work on surface saline water modelling in the Sundarbans region and find a relationship between salinity intrusion and the cultural landscapes changing pattern in the mangrove wetland ecosystems. This is why data samplings have been collected from river waters and changing landscapes field areas in the Sundarbans region. There is an ongoing interdisciplinary research project by name Sundarbans Biodiversity Conservation Project (SBCP). Some relevant data has been collected and used by SBCP, and will also be used in this study. Water salinity related data has been collected from IWM (Institute of Water Modelling) of Bangladesh. Besides these, data has also been collected through personal interviews with the stakeholders and management authorities at field level. The secondary data and Sundarbans related environmental information have been collected from different university libraries and NGOs working in the same field within Bangladesh and abroad. The Sundarbans resources and tourism related information have also been collected through personal interviews with direct beneficiaries and stakeholders. Tourism is one of the harmful activity for the fauna and flora so data and information has also been collected from the tour operators and tourists within the forest as when data collection was been done. About 21 tour organisations are involved in the Sundarbans tourism operations and annually 120,000 tourists visit the heritage site in the Sundarbans (Chaves, 2002; BPC, 2002; BPC, 2001). This information was summarised based on a survey carried out 2003 (January-April). The study used multiple techniques for data collection. The techniques used are sample surveys, semi-structured interviews, and focus group discussions, transect walk and observation in the case areas. Basically three different types of data have been collected through these collection techniques. For environmental data and information, there was a long discussion with the forest officials working in the field such as in the forest stations surrounding the Sundarbans.

The survey was done between February-July 2003 at different intervals and took into consideration the wet and dry seasons. The tested results from SRDI-Dhaka have been used in water salinity modelling.

To aid in acquiring field level data, a set of questionnaires had been developed which covered the information necessary for this study. There were 40 basic questions, including both open structured and semi-structured for the stakeholders. Open discussions have been made with administrative, managerial and business groups, tour operators, tourists, NGOs, and relevant research organisations. There were some trips with the tourists and shrimp farmers and resource users in the Sundarbans for collecting information through personal interviews. Beside these interviews, there was a special observation with the stakeholders involved with the Sundarbans for their every day life information for the environmental investigation. Besides questionnaires PRA (Participatory Rural Appraisal) and RRA methods were also followed for accurate data collection from the stakeholders (PRA, 2002). Non structured questionnaires surveys, discussions and interviews were employed to obtain data and information from important administrative, decision and policy makers and research personalities who are working on saline water, Ganges water sharing, and mangrove forest and management of coastal ecology in Bangladesh. For the sample collection, 75 samples of water and soil from 9 important sites inside and outside the Sundarbans were collected and tested in the Soil Resource Development Institute (SRDI) laboratories in Dhaka and the results have been shown in graphical presentation using EXCEL, SPSS, GIS ArcView, and MATLAB software.

Secondary data and information such as in published books, journals, statistical data, research reports, and maps were collected from various Government and non Government organisations, universities, educational institutions and research organisations. The secondary data as well as published materials and relevant books on the Sundarbans were collected from book markets, universities libraries and research organisation in Dhaka, and Khulna. Some primary and secondary data and information; and maps were obtained from international environmental research organisations and water modelling institute such as Earth Observation Research and Application Centre (EORC), Japan, Global Digital Data from Pennsylvania State University, USA and USGS Louisiana, USA. Information on resource extraction, environmental degradations, saline water, soil and revenue within the Sundarbans were obtained from the Ministry of Environment and Forest and Institute of Forest Research in Chittagong, Bangladesh Bureau of Statistic (BSS), Soil Resource Development Institute

(SRDI), Saline Water Research Centre Khulna, Department of Forest in Dhaka, Sundarbans Biodiversity Conservation Project (SBCP) in Khulna, EGIS in Dhaka, Institute of Water Modelling (IWM) Dhaka, BIWTA, BWDB, BARC libraries, BIDS, BIWTA, IUCN, UNESCO, UNDP and Sundarbans related research institutions, universities and NGOs in Bangladesh. The Satellite imageries MSS-5 TM 1980, TLS-5 1985, LANDSAT-5 TM BAND 2 1991, LANDSAT-5 TM BAND 2 3 4 colour, LANDSAT-5 TM BAND 2 3 4, 2002 colour (collected from SPARRSO Ministry of Defence of Bangladesh, Satellite and Remote Sensing Centre Bangkok, Thailand.) have been observed in papers and the areas/features depicted in them visited physically. Methodological analyses have also been carried out on the satellite imageries to understand the landscapes changing pattern(s) in the mangrove forests and wetlands region. Journals and relevant research reports study area from NGOs, university libraries, international and national organisations and various governmental offices from Dhaka and outside of Dhaka in Bangladesh. GISArcView 9.1 applications have been introduced for mapping and data visualisation on the Sundarbans mangroves wetlands ecosystems. Papers and publications of international organisations and journals have been used through internet and BTU libraries.

After completion of data collection, relevant data was processed and analysed both manually and on the computer. MS excel, SPSS, GISArcView 9.1 and MATLAB version 7.1 software were used for computer based analysis, data visualisation, graphics and development of Fourier polynomial models. The results of interpretation are presented in tables and graphs, visualisation maps and models. The methodologies followed for the research are presented in the following steps. The concept development was based on the research project proposal and conceptualisation of problems identification, selection of the study area, and preparation for reconnaissance survey, realising and understanding existing conditions, field investigation and data collection. Three types of data have been collected primary data from field investigation, secondary data from institutions and published materials and tertiary data from recognised published volumes from university libraries and research institutions. Finally data processing, analysis and interpretation were done using relevant software in the development of modelling and final report presentation.

1.3 Objectives of the study and organisation of the thesis

The objective of the study is to contribute to the preparation of an adequate management plan of cultural landscapes and surface water salinity in the Sundarbans, in combination with sustainable use of natural resources and water salinity modelling which will contribute to protect the mangrove wetlands ecosystems and ensure long-term conservation of cultural landscapes and wetlands ecosystems in the south-western region in Bangladesh.

The specific objectives are as follows;

- To identify problems with the current situation of Sundarbans mangrove wetlands ecosystems. The problem analysis is done primarily from an ecological perspective. With additional socio-economic and transboundary governance analysis, there could be a better understanding of the Sundarbans coastal mangrove wetlands ecosystems and means of improving management policies to protect these globally significant wetland resources.
- To analyse of the present inadequate water salinity management systems, cultural landscapes, mangrove wetlands ecosystems management and conservation strategies for environmental resources in the Sundarbans.
- Investigation of the problems of landscapes changing pattern with in soil and water salinity intrusion such as water quality, vegetation covering and shrimp cultivation at the specific case areas in the Sundarbans.
- Explore the concept of cultural landscapes protection, and mangroves wetlands ecosystems management; research applicability of the concept to the site.
- GIS application and environmental data analysis and visualization for having the real scenarios of the Sundarbans mangrove wetland ecosystems.
- Time series modelling of water salinity (NaCl) in the Sundarbans rivers and analysing the model results. Fourier polynomial models analysis, forecasting the salinity trends and behaviour for different ecological zones in the Sundarbans mangrove wetlands for the development of mangrove wetlands ecosystems.
- Water salinity Modelling using signal approximation by Fourier polynomials to describe the actual status and contribute to the preparation of a comprehensive management plan for the protection of cultural landscapes and mangrove wetlands ecosystems in the Sundarbans region.

The study will make recommendations on the future development of the site and its ecosystems, especially with regard to sustainable development, long-term conservation and the management of cultural landscapes and contribute to the drawing of an adequate national management plan for the protection of mangrove wetlands ecosystems in the Sundarbans region.

In the present research, an effort has been made to analyse the mangrove wetlands ecosystems and cultural landscapes changing pattern considering the salinity intrusion in the whole

Sundarbans area in Bangladesh. Based on the environmental impacts in the region salinity modelling has been considered as priority issue for decision makers to make adequate management plans for Sundarbans in respect to protecting the cultural landscapes and mangrove wetlands ecosystems in the Sundarbans. The study is organised into 6 chapters. Following a brief introduction, Chapter 1 outlines the goal and objectives of the study. For an understanding of mangrove background, the problems identification and specific objectives of this study have been discussed. The Sundarbans mangrove wetlands and its environmental problems, deltaic characters, tidal floods slack and ebb slack, river bank erosion and accretion, data collection methodology have been analysed. Chapter 2 studied the concept and understanding of cultural landscapes and mangrove wetlands, cultural landscapes of outstanding universal values and human layout and their distributions in tropic and subtropic areas, the factors and forces of changing features of cultural landscapes, mangrove wetlands performance as a dynamic network and functional benefits, socio-economic and cultural aspects of wetlands and cultural landscapes, analysis of mangrove wetlands ecosystems and discussions on cultural landscapes and the challenge of mangrove wetlands ecosystems. Chapter 3 deals exclusively with the Sundarbans study area which is the case base studies of this research. It includes an overview and distribution of mangrove wetlands in Bangladesh, the geographical location and climatic condition, hydrology and geological formation of the Sundarbans, deltaic mangrove ecosystems as unique marginal and fragile systems, salient features of the deltaic mangrove ecosystems; and world heritage site and tourism development and as an analysis of their socio-economic importance and local interdependency correlation. In the same chapter the existing management strategies and pressure, problems and substantial use of natural resource has been recognised as one of the major threats to ecosystems. The present environmental degradation in the Sundarbans areas due to shortage of fresh water and withdrawal of the Ganges water from upstream at the Farakka Barrage in India and the negative impacts on the mangrove ecosystems and cultural landscapes in the down stream in the Bangladesh Sundarbans regions have been identified and analysed. In Chapter 4 the modelling of surface water salinity in the Sundarbans areas is comprehensively analysed. There are 13 important rivers which have been selected as water salinity sampling points and at every river point salinity samples have been collected and analysed based on salinity intrusion rate on each point. The influential 13 rivers have been chosen for modelling and include the Passur-Mongla River, Baleswar-Bogi River, Selagang-Harintana River, Sibsa-Nalianala River, Bal-Jhalia River, Passur-Passakhali River, Betmargang-Kathka River, Chunar-Munchiganj River, Kholpetua-Kobadak River, Notabakikhal-Notabaki River, Arpongasia-Deboki River, Nilkamal-Hironpoint River and Malancha-Mandarbaria River. Based on the scientific sophisticated data collection from those rivers in the dry season and wet season, the time series models approach have been analysed using Fourier Polynomial Models. In the use of Fourier Polynomial Models, these 13 rivers in the Sundarbans mangrove wetlands, became representative of the whole mangrove wetlands area and depict river salinity behaviour in the region. The salinity behaviour Models were developed and compared and analysed with other points. The seasonal and yearly model behaviours were analysed considering the seasonal upstream fresh water supply, yearly rainfall, temperature and others climatic factors and environmental parameters. The Fourier Polynomial Models were developed at the 13 important rivers and the strategically important locations where long-time data is available. Through this polynomial modelling, a discussion and analysis has been done using statistical approaches for forecasting the situation. These analyse are used in observations of time series data and yearly salinity behaviour. As part of this study, a time series salinity modelling was done which will aid in forecasting future salinity trends in the regional ecosystems. The results of surface saline water modelling in the Sundarbans areas have also been discussed more concisely and critically in Chapter 4. The elaborate discussion tried to find out the goal oriented solution for ecosystems based management of the Sundarbans mangrove wetlands. In Chapter 5 due consideration and observation have been given some constructive integrated proposals and recommendations which have been recognised for future implementation and ecosystems development and which will carry out a way of sustainable fresh water supply and natural resource management in the Sundarbans. Finally in Chapter 6 which is the concluding chapter of my thesis, summary and concluding remarks have been highlighted. The summary of this research work shows the fundamental solution and policies for the adequate management of the Sundarbans mangrove wetland ecosystems.

Chapter 2
Cultural Landscapes and Mangrove Wetlands in the Tropical Zone

2.1 The concept of cultural landscapes and the understanding of wetlands

The term of landscape, which means both "perception of aesthetic view" and "mosaic of interacting natural elements", seems to be a source of discussion even in landscape ecology (Naveh and Lieberman, 1984). A landscape is a natural topography and a set of heterogeneous characters, which is perceptively, linked to the existential being of the body in societal space and a cultural code for living, and a space for human praxis, and a mode of dwelling (Tilley, 1994). The term landscape was *regio-regionis* which emphasised a geographic aspect and scenery. The concept of landscape was reintroduced in Italy in the 15th century with new interest (Ingegnoli, 2002). The recent origin of thought clearly explained the naturalistic view of landscapes as a backdrop of activities. A cultural view of landscapes as a highly specific, symbolic and cognitive ordering of space offers far more potentials in understanding (Fairbrother, 1974). Cultural landscape as an area of exceptional natural beauty, containing superlative natural phenomena are means of linking local landscapes, actions events and experiences together, providing a synthesis of heterogeneous phenomena (Head, 2000 ; Buhman and Ervin, 2003). There is a wider relationship between social practices and landscapes. The environmentalists, anthropologists and archaeologists have been interested for a long time in the relationships between people and the landscape conceived by environmental milieu (Figure 2.1). The local people and their landscapes are drawn on in the daily lives and encounters. The landscape is embedded in the social and individual times of memory. Figure 2.1 shows an integrated correlation among the people-landscape and ecosystems such as relation between people and landscapes, people and ecosystems, landscapes and ecosystems. Analysis this integrated triangular relationship framework, the definition of cultural landscapes can be considered based on these three elements of environment. Therefore, cultural landscapes reflect interactions between people and their natural environment over time and space. The term *kulturlandskap or Kulturlandschaft* would therefore immediately explains itself and today the concept has become so well defined and become a term on its own (Birks et al. 1999). Narrative is a means of understanding and describing the world in relation to culture, heritage and civilisation. The great scholar bio-geographer Alexander von Humboldt was the first to give a scientific definition in 1840 to the concept of landscape (Landschaft) as “the total character of a region of the earth”, which is still considered acceptable. Surface (landscape) is basically nature and culture is a fabric of human peculiarity.

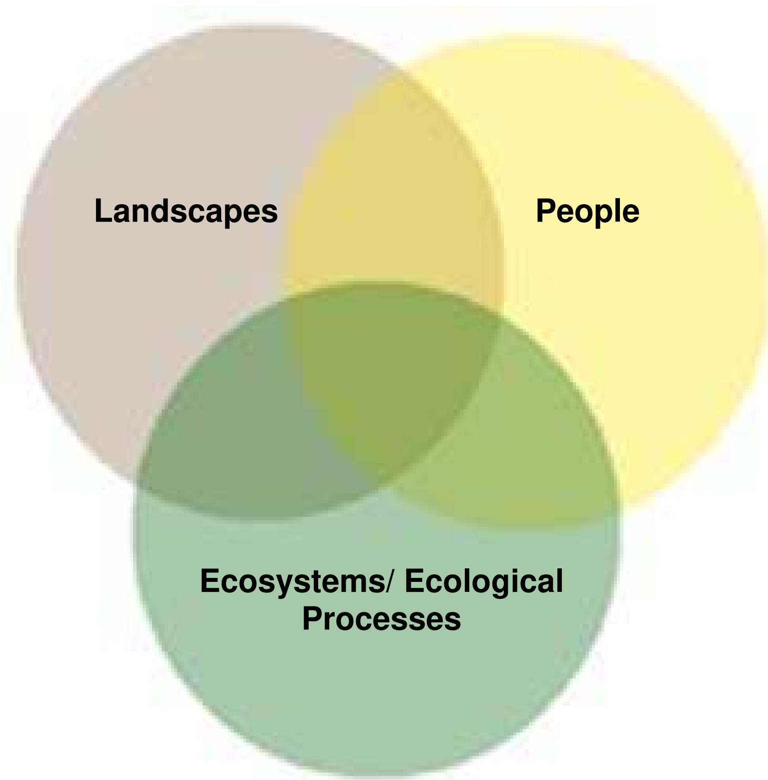


Figure 2.1 The environmental relationship framework

Presently, cultural landscape is the most spectacular global issue for economic growth and balance ecosystems. By the late 20th century landscape had been embedded with a range of meanings and values (Miening, 1979). The general meaning of landscape exists at two levels; every day landscape and iconic landscape. The every day landscape refers to the ordinary landscape, which is normally used in every day life whereas iconic landscape refers to landscape iconography. Wetlands are a major feature of the landscape in almost every part and in most important ecosystems on the earth. Nowadays, wetlands are described as the heart of the landscape and it is called the biological centre because of the extensive food chain and rich biodiversity. Wetlands function as the downstream receiver of water and waste from both natural and human sources (Ahmed, 1995; Annette, 2000). The Ramsar Convention defined wetlands as "areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salty, including areas of marine water the depth of which at low tide does not exceed 6 metres" (Ramsar Bureau, 2005). Wetland sites are unique because of their hydrologic conditions. They serve as reservoirs for water and help in ameliorating floods and drought. Cultural landscapes have gained recognition because of their outstanding universal, natural and cultural values. "Different types of cultural landscapes can be recognised around the world from the Mongolia semi-desert Prairies to the upland Prairies of the Southern-European mountains, from the olive orchards of the Mediterranean, to the rice terraces of the Philippine mountains and the Sundarbans mangrove wetlands in Bangladesh and India where human presence and its related influence, modification and disturbance have a long history of co-evolutionary process" (Farina, 1998). The World Heritage Convention (1972) has defined three categories of cultural landscapes (UNESCO, 1999). The most easily identifiable is the clearly defined landscape designed and created intentionally by humans. The second category is generally evolved landscape. This results from an initial social, economic, administrative, or religious imperative and has developed its present from association with and in response to its natural environment. There are two subcategories of such landscapes: a) A relict landscape; an outstanding example is the Hortobagy National Park in Hungary. The Sundarbans mangroves (a Ramsar site) can be categorised as a relict cultural landscape (Islam, 2003). b) A continuing landscape; there is an example of continuing landscape in Europe: Öland in Sweden (Droste et al., 1995). The final category is the associative cultural landscapes where powerful religious, artistic or cultural associations of the natural element exist rather than material cultural evidence, which may be insignificant or even absent. The Uluru-Kata Tjuta national park is of outstanding significance to Australia's indigenous people (Droste et al., 1995; Rössler, 2000; UNESCO, 2000; 2001). A forest or wetland which is frequented and which natural resources are utilised by people directly could also be classified as a cultural landscape. Based on this criterion the Sundarbans has been considered both as a cultural landscape and a natural heritage site.

2.2 Mangrove origin, diversification and distribution in the world

There are some theories and hypothesis of the origin and distribution of mangrove in different part of the world. But to recognise and identity of the actual time and space of mangrove species is quite hard for the scientist. In general the origin of the mangroves and some of the imagine routs to the new world which showing fossil sites, as far as possible believed that the end of Cretaceous (100-70 Ma). According to Chapman (1975; 1976) the migration routes through the Tethys Sea and to the new world it would be supported by the fossil investigation and it is acceptable than the Trans-Pacific migration routs (Figure 2.2). It is very difficult to say the exact time when the mangroves appeared and diversified in the geotops. Until now there are some contradictory hypotheses concerning the mangroves distribution and origination. According to Rull in 1998 the Nypa mangrove plam is the oldest mangrove of the region and from the cretaceous period. During the Eocene period the Nypa flora extended to higher latitudes. It was very common along the north eastern Brazilian coast (Wijmstra, 1969).

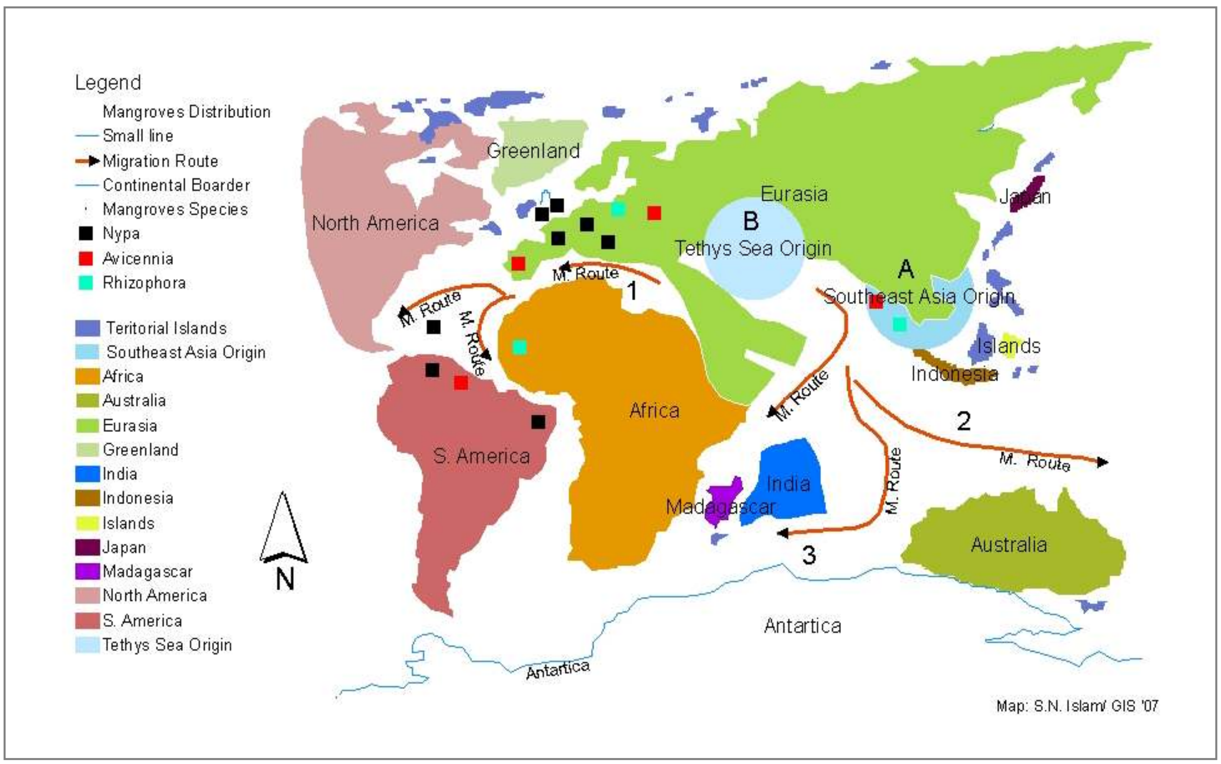


Figure 2.2 Origin of mangroves and distribution in the world (after Lacerda, 2001)

(Note: A - Southeast Asia origin centre, B - Tethys sea origin centre. 1 - Migration through the Tethys Sea to the Atlantic and TransPacific migration, 2 - Migration from the Tethys Sea to Southeast Asia and the Atlantic through the Panama isthonus, 3 - Antarctica / South Africa and surrounding islands route).

"The rich mangrove flora and fauna for Indo - Pacific acquired its mangrove species about 80 million years ago. The genera *Rhizophora* and *Avicenna* are thought to have evolved earlier and may have spread through the Tethys Sea (which is now called the Mediterranean Sea), east coast of America and west coast of Africa. In general, the hypothesis of the distribution of mangroves in the American continent has been developed in Pleistocene time. Figure 2.2 shows the location of migrations and the origin of mangroves. For example the common species *Nypa frutican* was alone in the Caribbean basin to north-western Brazilian coast. The Eocene mangrove suddenly disappeared at the end of this epoch and post Eocene species was totally different than before. The two kind of species of post Eocene period that is *Pelliciera* and the post Eocene mangles where *Rhizophora* prevailed and associated with *acrosticchum*. It is suspected that perhaps they have reached the Caribbean by early Eocene (50-55 Ma). Contemporaneous to Pelliciera, extensive *Rhizophora* and *Avicennia* forests covered the northern South American coast. The Americas show abundant mangroves which have confirmed the early Eocene as the probable date of mangrove arrival to the new world" (Figure 2.3) (Lacerda, 2001).

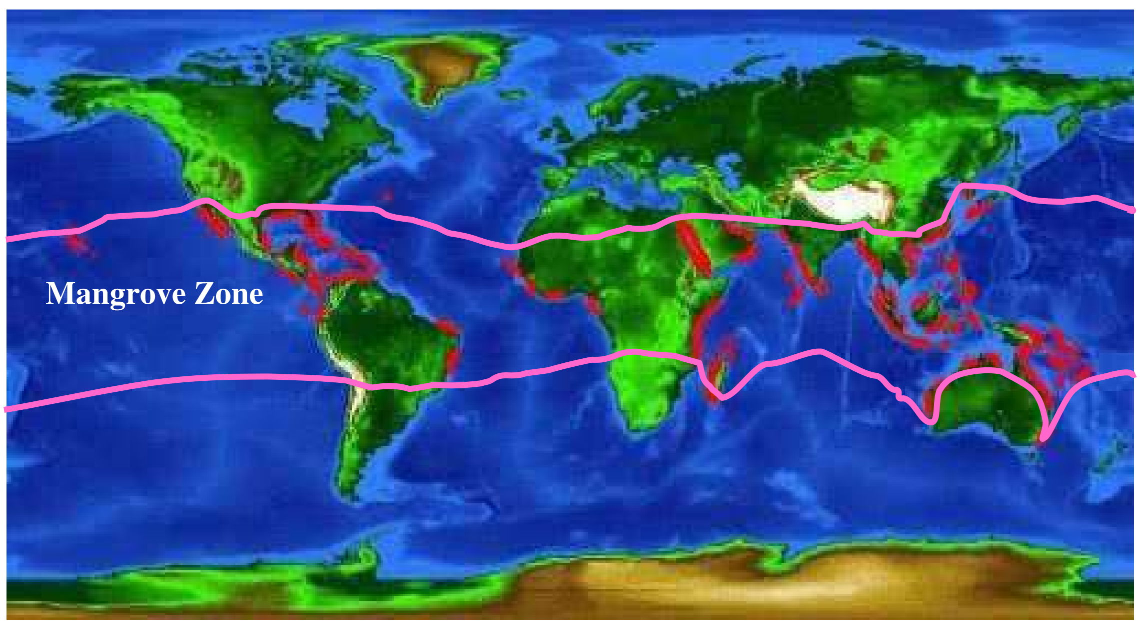


Figure 2.3 The present mangroves distribution and location in the world

There are different views on the origin of mangroves and some of the proposed routes to the new world. The possible origins and migratory routes of mangroves are depicted in Figures 2.2 and 2.3. Mepham (1983), one of the mangrove experts made very strong argument against some hypotheses of the origin of mangrove flora in East Asia and their distributions. According to Lacerda (2001), Tethyan was the region where mangroves first accumulated and some are still present in this region. According to Duke (1995), the origin and evolution of *Avicennia* ancestor appeared during the early Cretaceous period, along the northwest coast of Gondwanaland. The distribution of mangroves along the American continent prior to the full development of glaciations in the Pleistocene seems to reflect the climatic conditions of that time (Lacerda, 2001). Considering the world distribution of mangroves the highest dominating part of the world is the south and south East Asia where 42 % of mangroves are found and the second highest part is the American continents where 27 % of mangroves are found. Only 15 % of mangroves are found in West Africa and 10 % in Australia and only 6 % are found in East Africa and the Middle East areas (Figure 2.4).

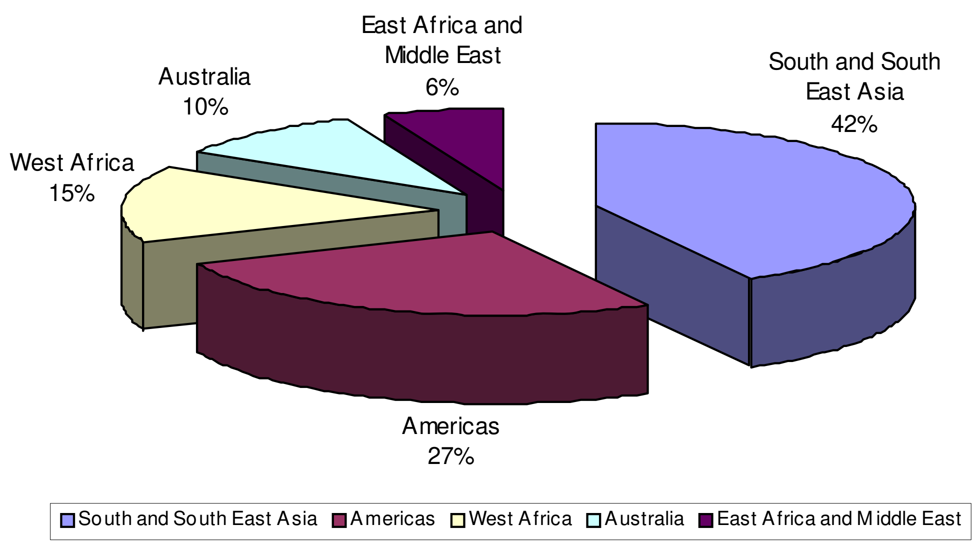


Figure 2.4 Mangrove distributions according to the region

Until now there are 70 species of mangroves that have been recognised in the world whereas 37 species are found in Australia and the Asia-Pacific region. This represents 52 % of the world mangrove species. In the Sundarbans mangrove forest, 66 mangrove species have been recognised, where 36 are mangrove species and 30 are mangrove obligate plant species (Appendix 2). By comparison, in America and Africa only 7 to 8 obligatory mangrove plant species are found, while in the Indo-West Pacific region, this is typically 20 to 40 species (Appendix 3). In this sense, Sundarbans is very rich in mangrove biodiversity considering to the other parts of the world. The distribution of mangroves species in different part of the world has been shown and elaborated discussion from the economic point of view and ecological consideration has been discussed in the sub chapter 2.3.1. Particular interest has been shown to a number of wetlands around the world with regard to their extent uniqueness and attributes. They include coastal and inland deltas, riverine wetlands, salt marshes and mangroves, fresh water marshes, and peat lands. They are found on every continent except Antarctica and in very rough climes from the tropics to the tundra. The world mangroves dominating countries are Indonesia 24%, Brazil 7%, Australia 6%, Nigeria 6%, Cuba 4%, India 4%, Malaysia 4%, Bangladesh 4%, Papua New Guinea 3%, Mexico 3% and the rest of the world represents 35 % only (Figure 2.5). A total of 750,000 km² of wetlands have been registered with the convention on Wetlands of International Importance as of 2000 (Mitsch and Gosselink, 2000).

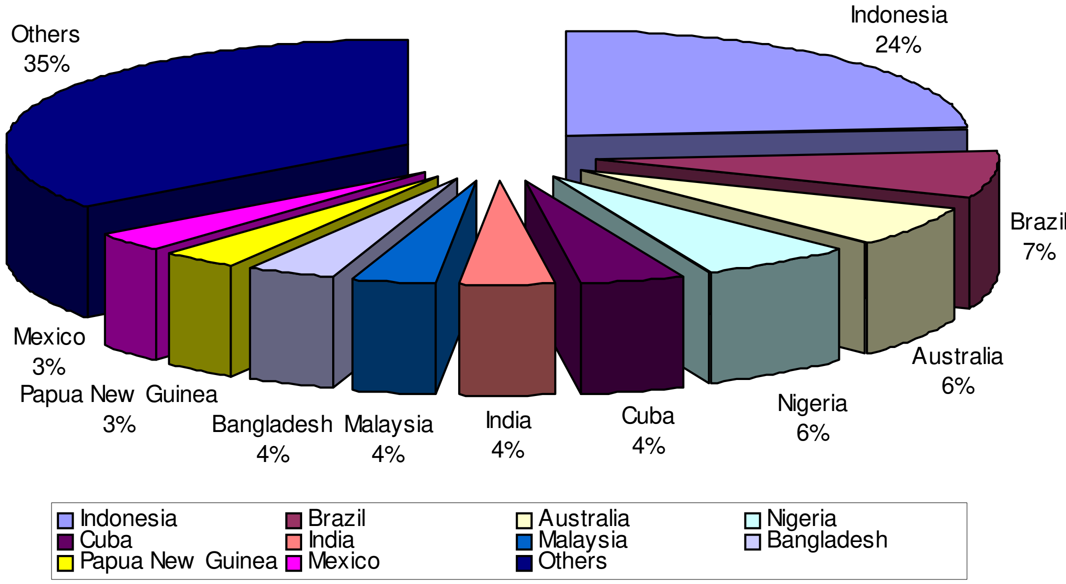


Figure 2.5 Mangrove distributions according to major dominating 10 countries

But the mangroves wetlands are found along tropical and sub-tropical coastlines throughout the world, usually between 25° N to 25° S latitude (Figure 2.3). The tidal salt marsh is replaced by the mangrove swamp in subtropical and tropical regions of the world. The word mangrove refers to both wetlands and to the salt-tolerant trees that dominate those wetlands. Approximately 14 million ha of mangrove wetlands that are generally dominated by the red mangrove species (*Rhizophora*) and the black mangrove species (*Avicennia*) (Mitsch and

Gosselink, 2000). The present world's mangrove vegetation cover has been estimated with an average of about 17 million ha, of which about half are in the Asia-Pacific region. The remaining 50 % is equally distributed in Africa (25 %) and the America (25 %) (Lacerda, 2001).

2.3 Challenge of cultural landscapes and mangrove wetlands ecosystems

Developmental activities in the wetland areas are mainly aimed at the reduction of flood level and the size of wetlands to facilitate irrigation and agricultural cropping development. Formerly, this was done naturally by wetlands and today it is done by dames and other hydraulic engineering measures. The flood protection embankments have hydraulic regime for sustainable management of wetlands (Ahmed, 2000). The process of continual losses of wetlands threatens to maintain life resulting in the reduction of wildlife habitat and replacing and displacing of wetlands based socio-economic activities. The threats are especially strong in the mangrove forests where huge areas are already converted to shrimp cultivation with disastrous consequences for the forests as well as for natural fishes (Khan et al. 1994; Dugan, 1993). In Bangladesh, the wetlands have suffered from human population and approximately 2.1 million ha of wetlands have been lost to flood control, drainage, irrigation development and other human developmental activities (Nishat, 1993). The scale of mangrove depletion and its causes vary from country to country. Coastal habitats and human stress are the vital reasons for exploitation of terrestrial aquatic and mangroves resources. Some main factors have been identified which are responsible for the decline of mangrove resources;

i) Mangroves converted to shrimp farms and fishing

For the last 40 years shrimp farming has been highly popular and profitable agro fishing business in the tropic and sub-tropic region. Mangroves in the South Asian countries especially in Thailand, the Philippines, Vietnam, Indonesia, Malaysia and Sri-Lanka have been converted to shrimp ponds and farms. Approximately 1000 km^2 of land now utilised for shrimp culture in Bangladesh was originally mangrove forest (Philip, 1999; Choudhuary et al., 1990). In recent years areas occupied by mangrove have declined by 34% in India, 45% in Bangladesh, 45% in Thailand and 99 % in the Indus delta in Pakistan (Siddiqi, 2001).

ii) Agricultural extension and urbanisation

Mangrove forest reclamation for agriculture is quite common in high population density countries in the tropic and sub-tropic region. High proportion of mangroves lands have been converted to agricultural lands. Historically the boundary of the present Sundarbans boarder was at the suburban of Calcutta and near Khulna in Bangladesh. In many countries the mangroves have been converted to urban areas, ports, airports, industrial estate, tourism complex and wild life watching tower. The Mongla port and Munchiganj were recently developed as urban growth centres (Siddiqi, 2001).

iii) Conversion of mangrove forest to salt pans and mining activities

In most countries the salt production industries have been constructed in the coastal zone and in the mangrove forest sites. Salt production areas in mangrove are spread over the tropical coasts of Asia and Africa including India, Benin, Thailand, the Philippines, Senegal, Brazil and Venezuela etc (Siddiqi, 2001). In the Sundarbans the oil and gas mining activities are on going practice which could be harmful for the mangrove habitats, biodiversity and ecosystems.

iv) Human influences and substantial use of mangrove resources

In the greater sense the mangrove world can be divided into two major economic zones such as Indian - Pacific Ocean mangrove economic zone, which is the larger economic zone in the world and where most of the mangroves dominated countries are situated. On the other hand, geographically mangroves world has been divided into 6 important zones (Figure 2.6) such as (i) Indo-Malaysia (ii) Australasia (iii) Western Coast of Americas (iv) Eastern coast of Americas (v) Western coast of Africa and (vi) Eastern Coast of Africa and Middle East.

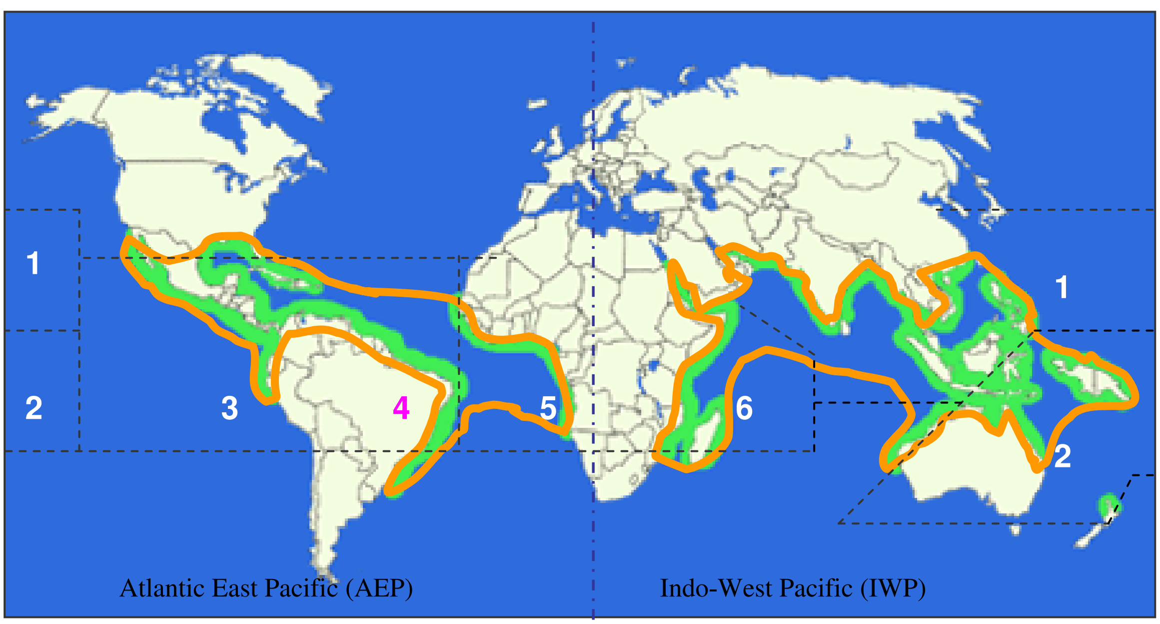


Figure 2.6 World mangroves economic zone (after Morley, 2000; Eco-world Organisation, 2004)

The countries that fall within the greater mangroves economic zone include Indonesia, Malaysia, Australia, New Zealand, Thailand, the Philippines, Taiwan, China, Vietnam, Myanmar, Bangladesh, India, Pakistan, Srilanka, the Maldives, Kuwait, UAE, Egypt, Kenya, Madagascar etc. The Atlantic-Pacific mangrove economic zone is situated in between these two oceans and covers mangroves dominated countries like Nigeria, Ghana, Togo, Ivory Coast, Gambia, Brazil, USA, Cuba, Mexico, Venezuela, Colombia, Panama, Costa Rica, and France Guinea. The coastal dwellers of these countries generally use the mangroves resources very openly.

v) Upstream diversion and dam construction

In many mangroves region withdrawal of fresh water from the upstream rivers for irrigation and other purpose has serious negative impact on mangroves and cultural landscapes. The extensive mangroves of Bangladesh, Gambia and Nigeria are facing the problem of upstream fresh water crisis.

vi) Tourism and recreational activities

Globally, coastal mangrove forests serve as an important spot of recreation and tourism. It is an attractive location because of sea beach, forest and water, which create wonderful combination of natural phenomena. Conversely this has a huge negative impact when a large number of tourists are attracted to the ecologically sensitive region without considering the value of ecosystems (WTO, 2002).

vii) Natural calamities

Cyclones, Tsunami and tidal surges are the most devastating threats for mangrove wetlands. (Huq et al., 1991; Salar et al., 1994). In recent times, the Tsunami has come as an issue of natural calamity. On the 26th December 2004 a Tsunami affected the Asia Pacific region, the Bay of Bengal and the Indian Ocean (Alam et al., 1998). The cyclone Cidr on 15th November 2007 destroyed huge mangroves and natural resources were severely affected and almost 10,000 peoples were killed in the Sundarbans coastal zone in Bangladesh.

2.3.1 Socio-economic and cultural aspects of mangrove wetlands and cultural landscapes

Wetlands are of great ecological and socio-economic importance. Wetlands also provide habitat for a variety of resident and migratory waterfowl, a significant number of endangered species of international interest and large number of commercially important ones. Wetlands also support a significant range of other activities such as extraction of reed, harvesting of edible aquatic vegetation and their products, medicinal herbs, shells etc (Salar et al., 1994). There are some 60 % of the world's population living within 60 km of the sea or in the coastal region and the socio-economic and environmental significance of the boundary between the land and the ocean is widely recognised (Brown, 1997). In Bangladesh over 10 million people live in the coastal region and offshore islands, although this rate is much lower than other coastal part of the world. The inhabitants of the coastal region are mainly involved in fishing, cattle rearing, traditional agriculture, forest resource collection and mangrove handicrafts making practices (Mondal, 1992). Chan et al., (1996) noted that the Matang mangrove in Malaysia plays an important role in the socio-economic sector. The 1400 ha Matang mangroves provides employment for about 12500 workers and generate an annual revenue of about US $ 42 Million (Chan et al., 1993; 1996). The Sundarbans mangrove forest is exploited for a range of forest products, of which most important are saw-timber, industrial raw materials, thatching materials and fuel wood. One of the most important non-wood forest products is *Nypa fruticans* leaf that is used for posts and frames of walls of local houses. The forest provides livelihood and employment to woodcutters, fishermen, honey and wax collectors, shell collectors, timber traders and other workers. It has been estimated that about 600,000 people are employed in every 6 months in a year (UN ESCAP, 1988; 1999). Furthermore over 6 million people depend directly or indirectly on the Sundarbans natural resources (Anon, 1995; MAP, 2000). This information indicates that the socio-economic aspects of the Sundarbans are linked with different communities (Alam, 2001). The annual value of the wood products removed from the Sundarbans mangrove forest is worth 100 million US dollars. The annual value of fish caught is 304 million US dollars, which is three times larger than the annual value of forest product (Alam, 2001; Hussain et al., 1994; Helalsiddiqi, 1999). The Sundarbans mangrove forest, Mekong river delta and mangrove are good examples of socio-economic interaction which depends on mangrove wetlands.

2.3.2 Benefits of mangrove ecosystems management

Ecosystems management is the only way to get past the piecemeal approach to environmental management. Traditional approaches tend to take the symptoms of one problem at a time, usually when problems become crises. The mangroves wetlands are affected by polluted water which is a threat for balancing the mangrove wetlands ecosystems. It becomes the most ecological priority issue to the communities. Some specific public beneficial issues are discussed here;

- Ecosystems management provides an opportunity to avoid ecological, social and economical crisis management.
- Ecosystems management would allow making a framework of flexible management and environmental information systems as well as a sustainable ecosystems management plan.
- Ecosystems management is a system which can minimise the negative impacts that occur within the environmental and resource management field.
- Ecosystem management allows natural resource management systems for a long term or a sustainable management of ecosystems functions of a specific area.

As a whole ecosystem management allows to minimize or reduce the future threats through forecasting and risk by addressing very potential environmental problems as well as anticipating catastrophe, and maintaining functional ecosystems.

2.4 Ecology and biological setting of mangrove forest ecosystems

Mangrove plants include trees, shrubs, ferns and palms. These plants are found in the tropics and subtropics on the river banks and coastlines. They are usually adapted to anaerobic conditions of both salt and fresh water environment and have developed growing roots which absorb oxygen. Considering the world mangrove characteristics, some important environmental settings have been classified in which mangrove colonization often occurs in different parts of the world.

a) The deltaic region which is dominated by the river flows and that extends seawards away from land, is one of the settings in which mangrove are found along a tropical coastline. Such important deltas receive a huge quantity of waters and sediments from the interior such as from the Mississippi, Ganges, Brahmaputra, Indus and Amazon River’s delta.
b) The delta which is dominated by the coastal tide does not extend into the sea but it is formed within the confines of the coast.

c) The mangroves colonize the heads of drowned tributary valleys and grow along the shores of lagoons behind bay barriers near the estuary mouth.

2.4.1 Physical factors of mangrove wetlands and forest development

In the case of mangrove forest development there are various types of biotic and abiotic factors that are responsible for development of floral and fauna species migration and distribution and luxuriance of the mangrove ecosystems. According to Chapman (1975) and Hutchings (1987), abiotic factors influence the establishment and development of mangroves in different parts of the world. These factors are explained below;

i) Temperature

The mangroves are very sensitive to frost in the freezing temperatures. The temperature regulates a large number of internal energy processes including salt regulation and excretion and root respiration. A very extensive mangrove only occurs when the average temperature of winter month is 20° C and where seasonal range does not exceed 10° C.

ii) Shallow shores

Mangrove plants require huge quantity of water. At the primary stage shallow water areas are suitable for the establishment of seeds and germination. The mangroves seedlings cannot anchor in deep water. Shore mangroves occupy a very narrow zone only.

iii) Mud substrate and aridity

Mangroves are able to grow on sand, peat and coral, the most extensive mangroves are invariably associated with mud and muddy soils. The high flow of the rivers, upstream water flows of rivers carry alluvial sands, mud to tidal flats thus, forming substrate for mangrove colonization and succession (Choudhury and Chaudhury, 1994).

iv) Salinity

Saline water or salt is the most essential requirement for mangrove production and development. As a whole salinity plays an influential role in mangrove germination, survival, growth, distribution, reduction and zonation of mangrove species. Different kinds of mangrove species development depend on different levels of salinity. The species *Rhizophora* is an obligate halophyte with poor production because of the reduction rate of salt. On the other hand *heritiera fomes* has strong preference for low salinity and its growth rate depend on tidal inundation and fresh water supply and the production rate can be decreased with increase level of salinity (Siddiqi, 2001; Brammer, 1999).

2.4.2 Ecosystem concept and adaptive mangrove ecosystems management

The present management of natural resources has entered in a period of change and uncertainty. The paradigm emphasises sustainable ecosystems rather than sustainable yield and focuses on management of whole systems for different kind of purposes. An integral part of ecosystem management is the realisation that the social system ultimately puts boundaries and constraints on our ability to manage the biological system. Some American geologists also highlighted and concurred with the famous Russian geologist Dokuchaev's theory on ecosystem, who also initiated and developed the concept of soil genesis and formation in 19th century. The proposed soil development was influenced by soil-forming factors such as climate, parent material, organisms, relief or topography and time (Vogt et al., 1996). Dokuchaev also expressed this relationship in a mathematical format; where he tried to define soil. Soil formation is the combined function of climate, parent material, organism, and relief and a period of time. The integrated functions with these elements of soil formation are depicted by the mathematical formula below;

$$S = f\,(cl,\ pm,\ o,\ r,\ t,\ \ldots\ldots\ldots\ldots)$$

Where *cl* - climate, *pm* - parent material, *o* - organism, *r* - relief or topography and *t* - time (Glink, 1927 and Vorg et al., 1996).

According to Dokuchaev the soil forming equation can be readily converted to an equation expressing the parts of ecosystems that should be considered as part of the management:

$$Ecosystems = f\,(S,\ cl,\ pm,\ o,\ r,\ t,\ \ldots\ldots\ldots\ldots)$$

Where *S* - soil, *cl* - climate, *pm* - parent material, *o* - organism, *r*- relief or topography and *t*- time.

Considering the definition of Dokuchaev and Vogt, the sophisticated definition of ecosystems can be structured on the following formula;

Thus ecosystems mean the functions of biotic and abiotic systems as shown in the following:

$$\begin{aligned} Ecosystems &= f\,(biotic\ and\ abiotic) \\ &= f\,(plant,\ animal,\ micro\ organism,\ water,\ soil,\ energy,\ \ldots) \end{aligned}$$

Ecosystems = f (S, cl, pm, o, mo, r, w, e, t, ...)

Where *S* - soil, *cl* - climate, *pm* - parent material, *o* - organism, *mo* - micro organism, *r* - relief of topography, *w* - water, *e* - energy and *t* - time.

Smith and Smith (2003) defend ecosystems in a similar way based on the argument that the interaction of the biotic community with the abiotic components bring about ecosystems development. The primary focus of ecosystem ecology is the exchange of energy and particulate matters. The exchanges from the surrounding environment into the ecosystems are inputs and that from inside the ecosystem to the surrounding environment are outputs. Hence, an ecosystem that is open to only the flow of energy is called a closed ecosystem whereas the one open to both flow of energy and particulate matter is an open ecosystem (Jürgensen and Muller, 2000; Smith and Smith, 2003). Smith also developed the schematic diagram of an ecosystem (Figure 2.7) which functions are similar to Vogt equation and its functions.

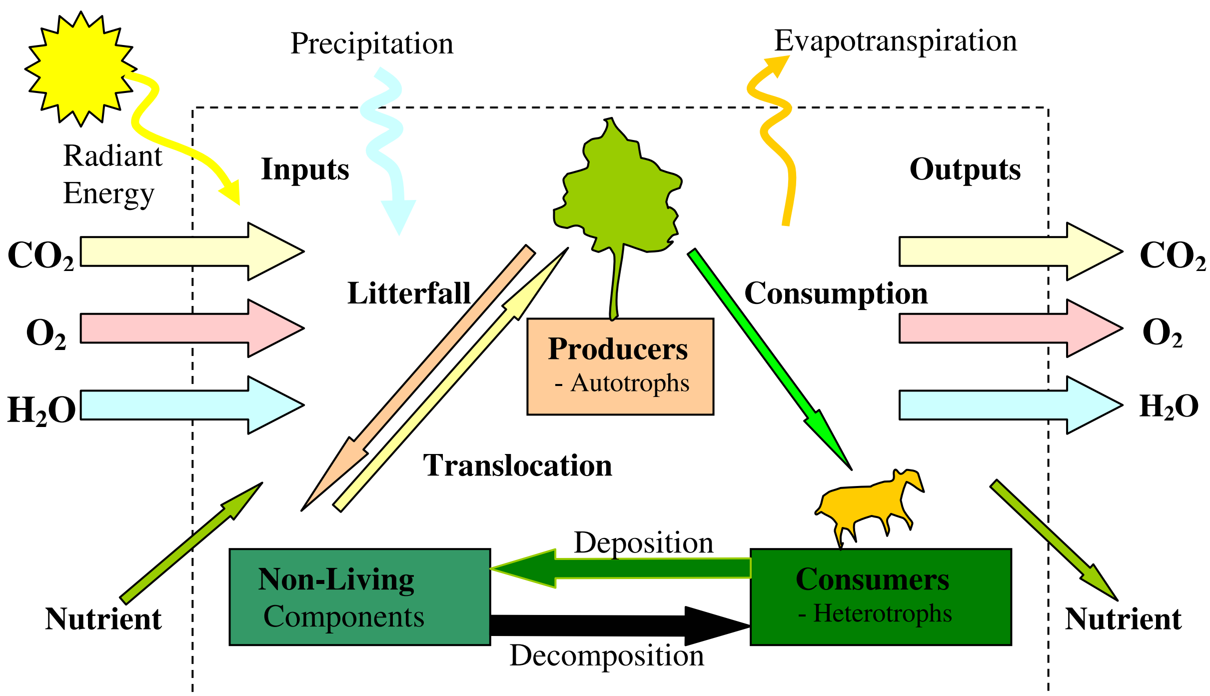


Figure 2.7 .The schematic diagram of an ecosystem (after Smith and Smith, 2003)

In Smith's schematic ecosystem's diagram there are three major components such as producers or autotrophs, consumers or heterotrophs and the non living components (Figure 2.7). The cycle of this diagram indicates interactions within the ecosystems and exchanges with the external environment. An ecosystem is fundamentally made up of a physiochemical environment called the biotope and a set of living species, animal and plants, called the biocoenosis. Furthermore Smith and Smith (2003) mentioned two types of ecosystems; the aquatic ecosystem and the terrestrial ecosystem with both consisting of three basic components namely, the autotrophs, the heterotrophs, and the non living components, which are essential elements in ecosystem development. Wetland ecosystems combine many structural and functional attributes of both terrestrial and aquatic ecosystems. A functioning that comprises all the transformations linked to the energy cycle, the cycle of water and soil or minerals. Figure 2.8 shows a combined relationship within atmosphere, water and soil cycling in wetland ecosystems.

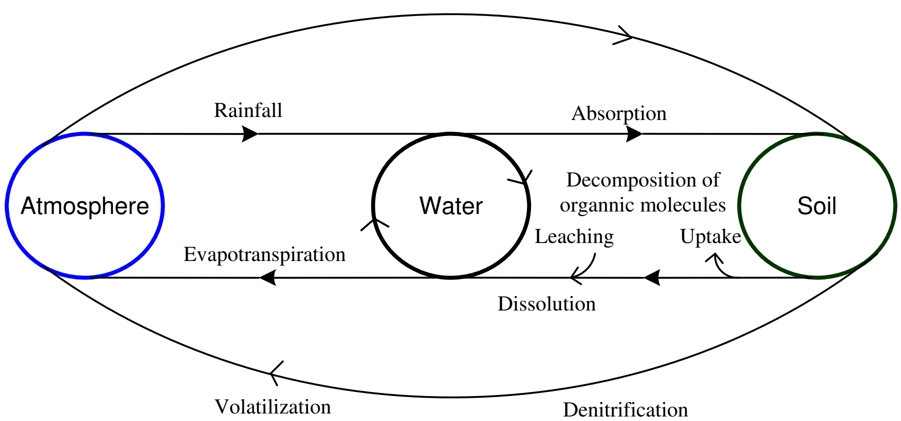


Figure 2.8 The general scheme of mineral cycling in a wetland ecosystems (after Dykyjova and Ulehlova, 1998)

Similar characteristics and relationships process within mangrove wetlands ecosystems can be seen in Figure 2.9. The mangroves are composed of trees and shrubs remarkably adapted to tidal and coastal land through their ability to live in poorly oxygenated sediment and can tolerate inundation by salt water through physiological chemical mechanisms (Morley, 2000).

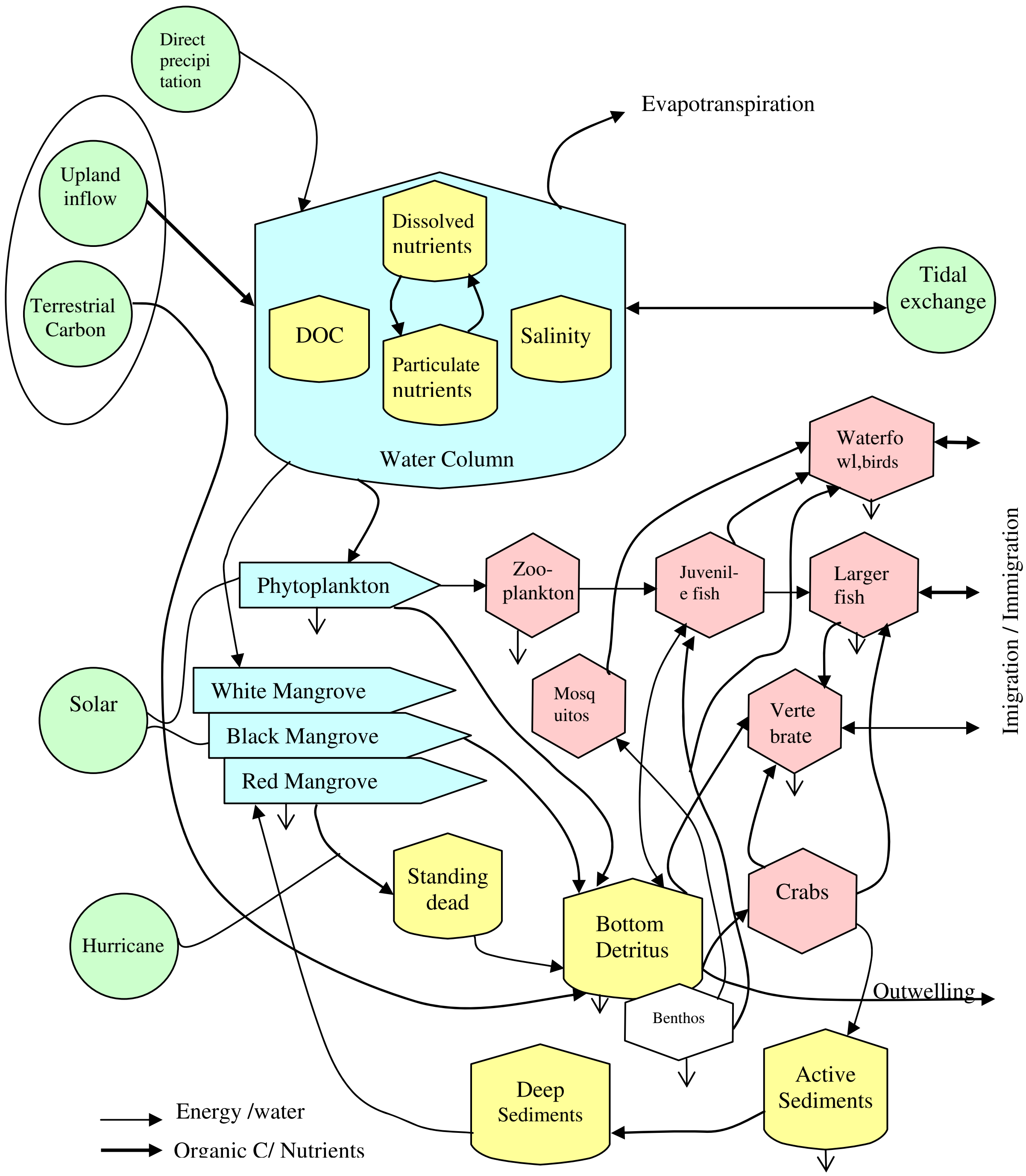


Figure 2.9 The conceptual model of mangrove wetlands ecosystems (after Mitsch and Gosselink, 2000)

The conceptual model of the mangrove wetland ecosystem diagram (Figure 2.9) shows the interconnection among fresh water inflow, tidal exchange, crabs, salinity and nutrients interaction within this process. In general the wetland ecosystems are physical links between terrestrial and aquatic resources (Figure 2.10). As such they receive from the following schematic way; the diagram (Figure 2.10) shows the integrated relationship between two types of ecosystems namely aquatic ecosystems and terrestrial ecosystems. In the figure arrows represent the transfer of materials and energy from one ecosystem to another.

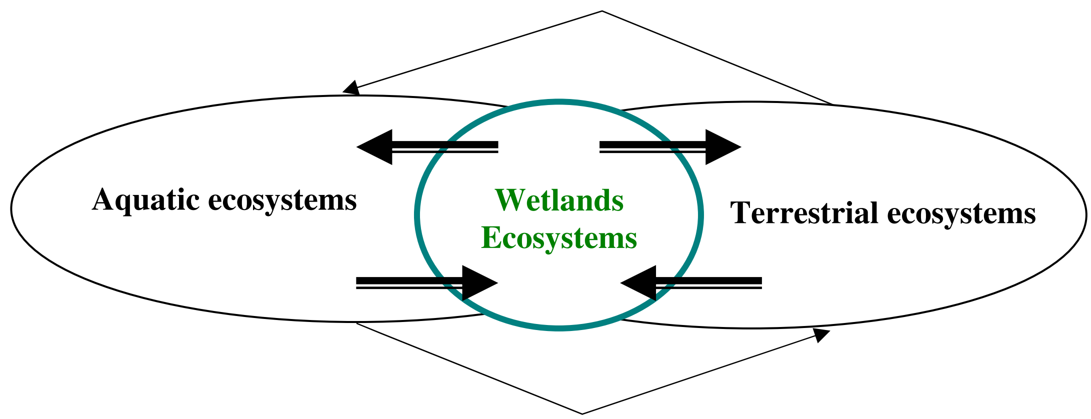


Figure 2.10 Ecosystems relationship (adapted from Erickson, 1994)

There are physical and dynamic links between terrestrial and aquatic resources and wetlands ecosystems (Erickson, 1994; Curry and Mcguire, 2002). Mangrove forest ecosystem management is one of the new approaches to environmental and natural resource management. According to Vogt et al., (1996) 10 potential principles have been identified that characterize the ecosystems approach. The principles are as follows; the definition of ecosystems management where the concept would be clear that humans are part of the ecosystems and consider their values and demand. Ecosystems management boundaries, Development of ecosystems management plan, policies, rules and regulations. Ecosystems management tools and technologies, collection of economic social and ecological information for decision making, recognition of ecological constraints, strong co-ordination between stakeholders and property owners, develop feedback mechanisms in all steps for promoting adaptive ecosystems management. Adaptive management is a term that occurs in most written discussions ecosystems management. It can be said that the meaning of adaptive ecosystems are measurable objectives in ecosystems functions and in social desire by scientifically using current data, monitoring and adjustment with management practice of ecosystem capacity (Vogt et al., 1996; Folk, 1998).

2.4.3 Mangrove wetlands performance as dynamic network and functional benefits

The mangrove wetlands have a unique mosaic of habitats with an extremely rich diversity of flora and fauna, and yet most of the forests areas are undiscovered. Mangrove wetlands also support the livelihood of millions of people from such diverse activities such as fishing, collection of natural honey, materials for thatching and fuel wood. Mangroves wetlands serve as filtering system to clean up polluted water, protect coastlines from erosion and act as barriers against storm surges besides providing people with wide range of staple food plants, grazing lands and fuel (Khan et al., 1994).

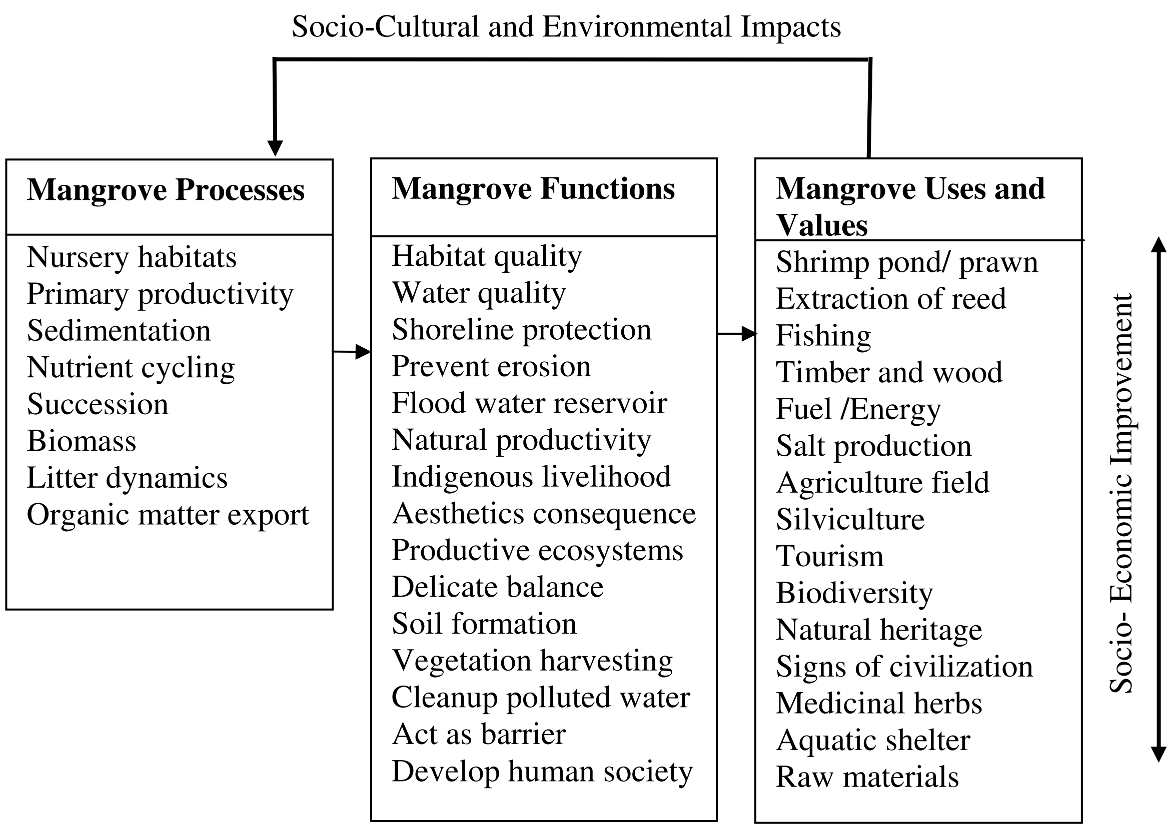


Figure 2.11 Ecosystem-human economy model (after Mitsch and Gesselink, 2000)

The process of mangroves and major roles and functions of mangroves ecosystems are as follows (Figure 2.11). Mangroves help in soil formation by trapping debris, They serve as sieve for rich organic soil washed down through river systems into the sea, provide appropriate ecosystem and nutrient shelters for fish, marine invertebrates, mollusca and birds, they contribute detritus which enhances the productivity of the ecosystem. The functions of mangrove ecosystems are divided into three categories (Figure 2.12). An estimated 181,327 km^2 of mangrove wetlands are found in 97 states and territories throughout the world (Appendix 1).

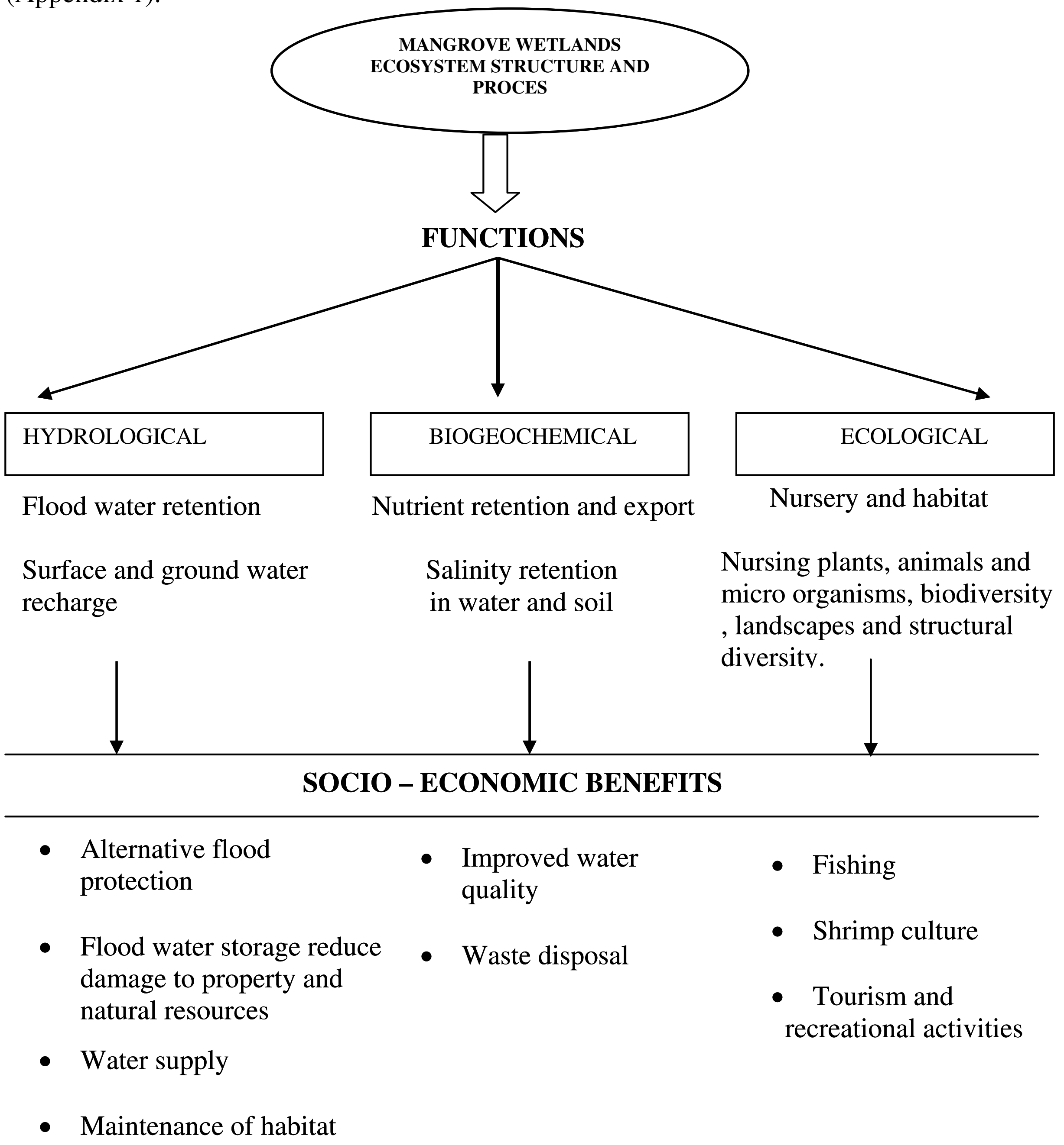


Figure 2.12 Mangrove wetlands ecosystems structure (afterTurner, 2001;Brouwer et al., 2001)

The dominant mangrove plants species are known for several adaptations to the saline wetland environment including prop roots, salt exclusion, salt excretion and production of viviparous seedlings (Khan et al., 1994).

2.4.4 Salient features of the deltaic mangrove wetlands ecosystems

The landscapes of the Sundarbans consist of a large number of fluvial and tidal geomorphologic features created by the GBM river systems. Mudflats are formed along the estuaries or riverbanks and are subjected to direct wave action, flow and turbulence of the water currents in the river. The lower parts of mudflat remains submerged during all high tides. Ridges or levees are found because of sediment deposition on the edge of riverbanks. The erosion and accretion balance in the Sundarbans has been estimated to be 146 km² for period 1960-1984 (Jabbar, 1992; Siddiqi, 2002). The causes of alluvial deposition are owing to the rise of the forest floor and irregular flow of tidal water as a result, seedling and mangrove regeneration do not take place properly (Coleman, 1964). A close network of interconnected tidal rivers and creeks dissect the Sundarbans in a north-south direction (Chaffey et al., 1985; Karim, 1988).

2.4.5 Deltaic mangrove ecosystems as a unique marginal and fragile system

The deltaic swamp of the Sundarbans is flat with micro topographical exceptions only. The sanctuaries are divided by a complex networking of tidal waterways, into 3 separate areas, which are of distinct interest; mud flats, small islands of salt and latent mangrove forests. This is an excellent and influential example of an on-going ecological progress; it displays the effects of a monsoon rain forest (Rashid et al., 1994; Christensen, 1984; Amin & Khan, 2001; Christensen, 1984). In the Sundarbans area this natural heritage site plays a role in opening up the regional culture, heritage, improvement of social condition and ecological balance in the coastal environment (Siddiqi and Baksha, 2001; Chowdhury, 2001).

2.5 The natural and human threats to mangrove wetlands ecosystems

The climatic change such as increase of global temperature, rainfall rating and local weather are the major threats to the development of mangroves in all over the world. It has been noted by many mangroves experts in the Asia-Pacific region that the natural hazards, salinity increase and fresh water depletion are the reasons for the severe depletion of mangroves in the Asia-Pacific countries (Siddiqi, 2001; Lacerda, 2001). On the other hand most of the countries in the Sahelian zone have gone through severe drought period since 1968 (Siddiqi, 2001; Lacerda, 2001). This climatic phenomena affected many coastal region and reduced the mangrove areas in Africa. A similar phenomenological affect has been recognised in American and Australian mangrove areas. Coastal areas offered specialised mangroves ecosystems, coral reefs, and sea grasses among others. Most of the mangrove swamps are near to the village settlements and inhabitants are totally dependent on the mangroves resources. The human and natural phenomenons cause damage and destroy the mangrove wetlands simultaneously in the tropic and subtropical region.

2.5.1 Unplanned policies and destruction of mangrove ecosystems

The natural resource management in the developing countries has become a more critical issue in recent years. Especially the coastal resources which are under Government control are not used properly and there is no adequate management plan for such sensitive vegetation covered areas. Owing to high forest resource demand by the people on a daily basis, they use these very desperately. Such situations have been observed in the coastal mangrove ecosystems in Asia Pacific region, Africa and Latin American region. The growth of population and huge resource use is one of the major causes of depletion of mangrove resources. In Latin American mangroves have also been destroyed owing to the similar reasons, now people are protesting to stop the destruction of the natural mangrove wetlands that had been supporting their livelihood. A practical example in Bangladesh is the Chakoria Sundarbans. It was a unique mangrove patch in the coastal district of Cox's Bazar in the south eastern corner of Bangladesh. Today its name remains only in memory of the coastal people in Chakoria. As early as 1976, there was no sign of mangrove vegetation and wildlife as it had been replaced by hundreds of shrimp farms, giving it the appearance of a saline desert. It was a much unexpected rush to cut the mangroves forest in the late seventies and early eighties when the Asian Development Bank (ADB) and the World Bank came forward with the investment to promote shrimp farming as a cash crop. Consequently, 210 km^2 of Chakoria Sundarbans mangrove wetland was destroyed because of unplanned polices (Philip, 1999; Siddiqi, 2001).

2.5.2 Management and conservation of world mangrove wetlands areas

The mangroves remained neglected and exploited in an unplanned way in most of the countries of the world. In fact the productive mangroves occur in Southeast Asia and they are managed under different silvicultural systems. In recent years, there has been some afforestation of mangroves in some countries (Siddiqi, 2001; 2002). In most Caribbean countries, legislation specifically covering mangroves is lacking, and in many countries of Latin America, regulation is more normal than practical. The management guidelines proposed four general categories for management such as a) Mangrove Conservation Reserve (MCR), b) Mangrove Forest Reserve (MFR), c) Mangrove Fisheries Reserve (MFR), and d) Damaged Mangrove Areas (DMA). Mangrove Conservation Reserve (MCRs) includes those forests set aside for conservation, tourism, recreation, and scientific studies. Thus, management of mangroves and its impact on regeneration and stocking of the forests are insufficient (Siddiqi, 2001). Anon (1987) and Siddiqi (2001) stated that the mangrove forest of Africa and Madagascar were never under a systematic forest management. The mangroves of Ghana in the Volta River delta area are now considered for methodological planned silviculture. The only suitable condition of mangrove forest can be considered in Tanzania. The exploitation of mangrove resources in Australia is extremely limited, forests are not exploited commercially. The threatened causes of sustainable management in the Indian Sundarbans are human influences. Almost 3 million people live inside the forests and they are dependent on forest resources (Choudhury, 1995; Siddiqi, 2001; 2002). The success story of the sustainable forest management in Matang is mainly due to intensive reforestation efforts. Other mangrove forests in Malaysia are not regularly managed (FAO, 1985). The mangrove forests of Pakistan are confined in the Indus delta and there is no management system in force (Annette, 2000; Siddiqi, 2001).

2.5.3 The threatened landscapes and mangrove wetlands ecosystems

The increasing salinity and the reduced of fresh water has been reorganised as one of the major threats for the health of the forest, of which the top-dying of Sundari (*Heritiera fomes*) trees is one visible evidence. The outbreak of top-dying disease of Heritiera fomes in recent decades is now a major concern among ecologists and forest managers (Hoque, 2001). Top dying of Heritiera fomes is considered to the most serious of all diseases and disorders of trees and a complex interaction of abiotic factors (Rahman et al., 1990, 1995; Chowdhury, 1995; Hartung et al., 1998). According to Rahman (2001) in the Sundarbans case the small management unit, which is called component, has been affected by top dying *Heritiera fomes* and other plants. There are 55 components still visible and 22 components have been badly affected. It has broken out as epidemic only in the last few decades (Rahman et al., 1990). Preliminary estimates of the top-dying *Heritiera fomes* state that approximately 17% of the stems are moderately or severely affected by top-dying disease, 265 km² areas are moderately and 210 km² areas are severely affected. The affected areas are located in the map (Fig. 2.13).

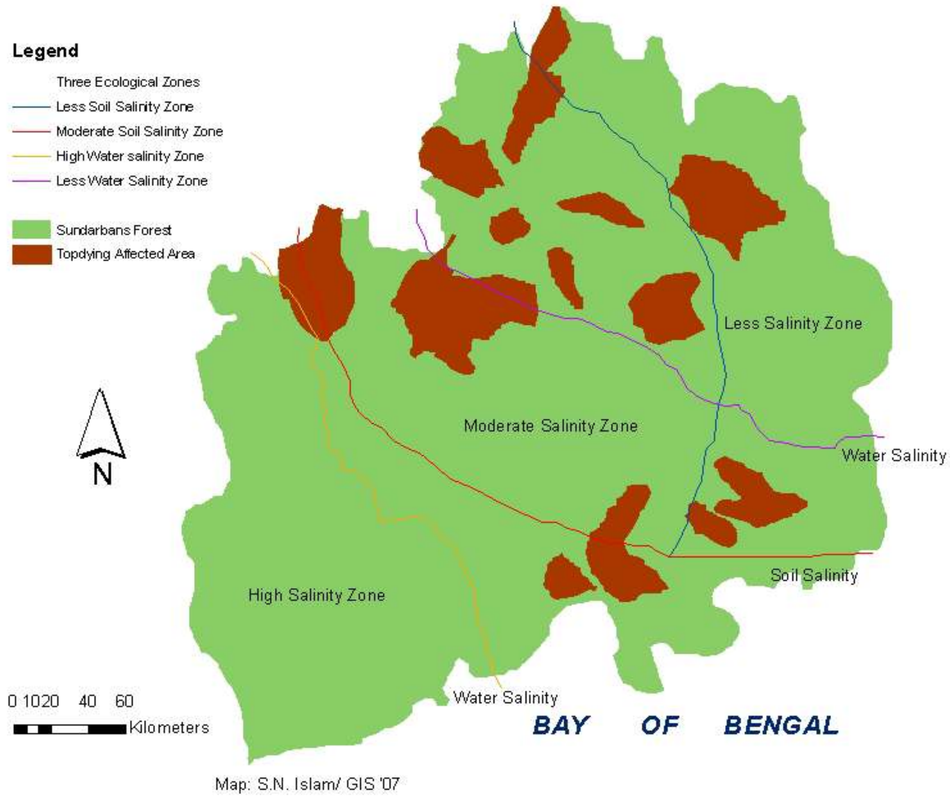


Figure 2.13 Heritiera type of forests are affected by Top-dying disease

It can be stated that salinity intrusion and damage of water quality and soil fertility in the Sundarbans are one of the major reasons for top-dying and die back disease although there are lots of contradictions and arguments behind this top-dying and die back disease. Each one of the components of the environment namely climate, salinity, fresh water supply, siltation, erosion, substrate and nutrient have a first order reaction on the flora and fauna of the ecosystems (Huq et al., 1999). Salinity of the intertwine zone has long been recognised as an important factor regulating growth, height and territory of mangroves (Bowman, 1917; Semeniuk, 1983; Hasan et al., 2001). Salinity undoubtedly affects the general health of mangrove and non-mangrove plants (Anon, 1973; Hossain et al., 2001). The detail information of salinity intrusion, its impacts and surface water salinity modelling and model results will be elaborately analysed and discussed in Chapter- 4.

Chapter 3
The Sundarbans Study Area

3.1 Mangrove wetlands in Bangladesh

The Sundarbans forest is the largest continuous productive mangrove wetland ecosystems in the world. It is located at the extreme end of the southern Ganges delta and it is about 10, 000 km² in southwest Bangladesh and West Bengal of India. A total area of 62 % lies in the Khulna region of the south western part of Bangladesh, while the remaining 38 % is in India (Siddiqi, 2001; Lacerda, 2001). This present Sundarbans area is approximately half the size of the area of mangrove that existed 200 years ago when the area was 17,000 km² the other half being cleared reason of human activities (Hussain and Acharya, 1994). The Bangladesh portion of Sundarbans covers an area of 6017 km² of mangrove forests, wildlife sanctuaries and sand bars, out of this 1874 km² are made up rivers, creeks and canals (Wahid, 1995). The land area of Bangladesh Sundarbans is about 4,017 km² (Katebi, 2001). The meaning of the Sundarbans in Bengali language is "beautiful forest", where Sundar means beautiful and Ban means "forest" (Choudhury, 2001). The exact origin of the name is very hard and difficult to determine. It can only be explained in terms of how the forest was named by Sundarbans. The most acceptable and popular theory is that it was named after its principal plant species Sundari (*Heritiera fomes*) which in Bengali means beautiful. The other theory is that this forest was named after the river "Sundhya" or "Samundraban" meaning sea forest. The great economist Kautillya described the forest as Kalikaban, and in the eighth century it used to be known as the Tiger coast (Choudhury et al., 2001). Later on the British adopted the present name Sundarbans for the mangrove forest (Choudhury et al., 2001; Siddiqi, 2002; Islam, 2003). The forest occupies a flat mud swamp which is submerged by high spring tide most of the year and almost all high tides during the rainy season (Hussain, 1992). The Sundarbans landscapes consist of a large number of fluvial and tidal lands, features created by the three mighty rivers, the Ganges, the Bramaputra and the Meghna.

A large number of channels and creeks flow into larger rivers in the Sundarbans. The largest of these rivers are the remains of the Ganges which has shifted eastward and the Gorai River the main tributary of the Ganges is connected to Passur River and indirectly with Sibsa River which are playing an influential role in the Sundarbans ecosystems. The Baleswar River is connected to the Ganges River in the eastern part of the forest and as a result receives lot of fresh water from it. The distance between the two extreme ends of the Sundarbans is about 100 km. while the vertical distance between the east and west within Bangladesh is about 80 km. By nature only the Sundarbans and the Chokoria Sundarbans have the main mangrove forest resources in Bangladesh and they are distributed in the south western part and south eastern part of the country (Ali, 1996). On the basis of the geo-morphology of the delta, mangrove wetlands forests can be categorised into the following types;

i) Fringe forest: It occurs along shoreline and tidal channels where there is a topographic slope and the inundating tidal water flows in the same direction.
ii) Basin forest: It occurs in the subside depressions.
iii) Riverine forest: It occurs on the islands and completely inundated by tidal water.
iv) Dwarf forest: It occurs in the form of sparse, scattered community of shrubs like mangrove species in carbonated environment and in arid areas.

On the other hand based on salinity distribution the mangrove forest of the Sundarbans can be classified into their district types, namely;

i) Fresh water forest: It occurs on the north and the eastern portion of the Sundarbans.
ii) Moderate salt water forest: It consists of the forest near the sea-face and where less saline is available in the monsoon and in the lean period.
iii) Salt water forest: It occurs in the west of the Malancha River where goran and gewa dominate the forest.

The entire Sundarbans mangroves extend to a large area along the coast and characterises the most spectacular environmental unit of the area (SRDI, 2000).

In transverse profile - from the mainland to the sea - the important geomorphic units of the Sundarbans delta include;

i) Distributary channels with lag, sub-arial and sub-aqueous leaves and tidal flat.
ii) Marginal marshy areas above mean tidal level
iii) Tidal sand bars and islands with their network of tidal channels
iv) Sub-aqueous distal bars and
v) Pro-delta clays and silts.

According to Sharmila (1989) the soils texture of the Sundarbans region has been classified into the following group; i) Clay soil, ii) Loamy soil, iii) Sandy loam, iv) Sandy soil and v) Silty soil. On the other hand based on chemical analysis the soils in this region can be classified into the different groups; i) Saline soil, ii) Saline-alkaline soil, iii) Non-saline-alkaline soil and iv) Degraded alkaline soil. Saline soils are found in the flood plains as well as in the natural depressions along the banks of the rivers and creeks. Saline-alkaline soils are found in high salinity affected areas (Anon, 1975; 1998). The mangrove flora and fauna plays a potential role in the creation of micro morphological features which are high significant for trapping sediments and mangrove seeds. On the other hand the morphology and evolution are controlled by an abundance of xerophytes vegetation (Bhattacharya and Chowdhury, 1985).

3.1.1 Geography and climatic condition of the Sundarbans

Most parts of the Bengal Basin and Ganges delta are floored with quaternary sediments eroded from the highlands on three sides and deposited by the Ganges, Brahmaputra and the Meghna rivers and their tributaries and distributaries. The Ganges River originated in Gangotri glacier in the southern slopes of the Himalayas and caries discharge from a catchment of about 865,000 km² in India, to Bangladesh (Figure 3.1) (Joseph, 2006). The area of GBM drainage basin is 1.76 million km² of which 62 % in India, 18 % in China, 7.5 % in Nepal, 7.5 % in Bangladesh and only 4% in Bhutan (Elahi et al., 1998). Geographically Sundarbans lies between latitudes 21° 31´ N and 22° 30`N and between longitudes 89° 01` E and 90° 18`E (Figure 3.2) (Katebi, 2001; Islam, 2003).

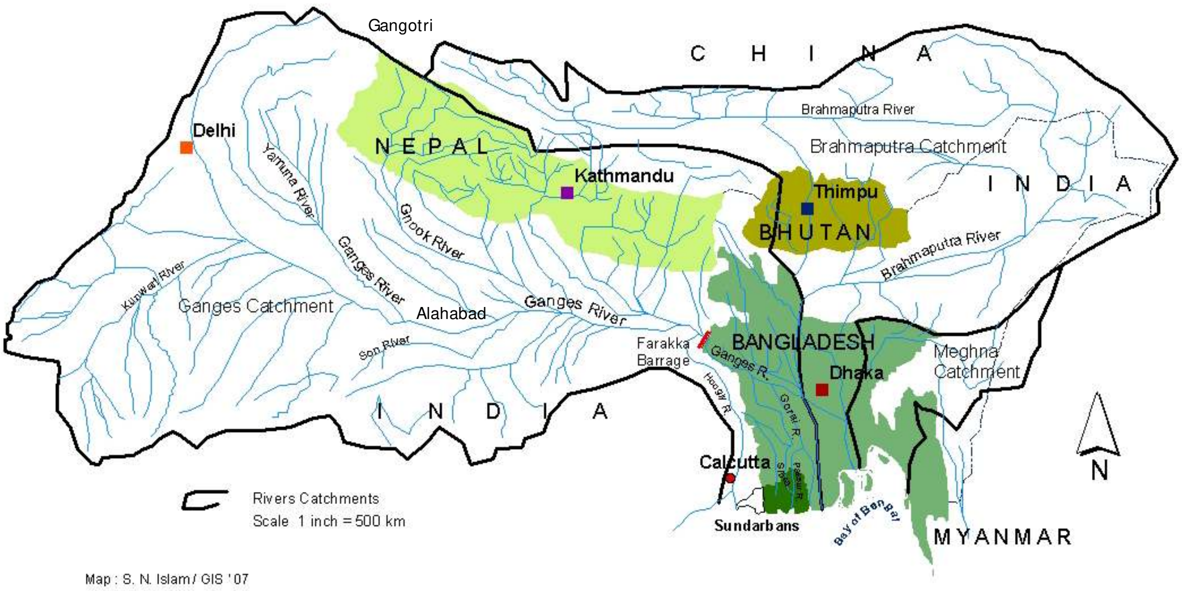


Figure 3.1 The geographical location of the Sundarbans in the Ganges catchment.

This river is the main source of silt deposits and delta formation in the Bay of Bengal. The Brahmaputra originates in the northern slopes of the Himalayas and travels into China to the east, then turning southward, it enters India before Bangladesh. Its catchment area is about 575,000 km² (Coleman, 1994; Haque, 1996; Das, 1992; Elahi et al., 1998). The Sundarbans region enjoys a humid tropical monsoon climate with proximity to sea as an added advantage. Temperature varies from 20° C in December-January to 34° C in June-July with an annual range of about 8° C. The Sundarbans mangrove forest spreads over the Ganges delta with an average elevation of 0.9 to 2.1 meters above mean-sea level (Bird, 1969).

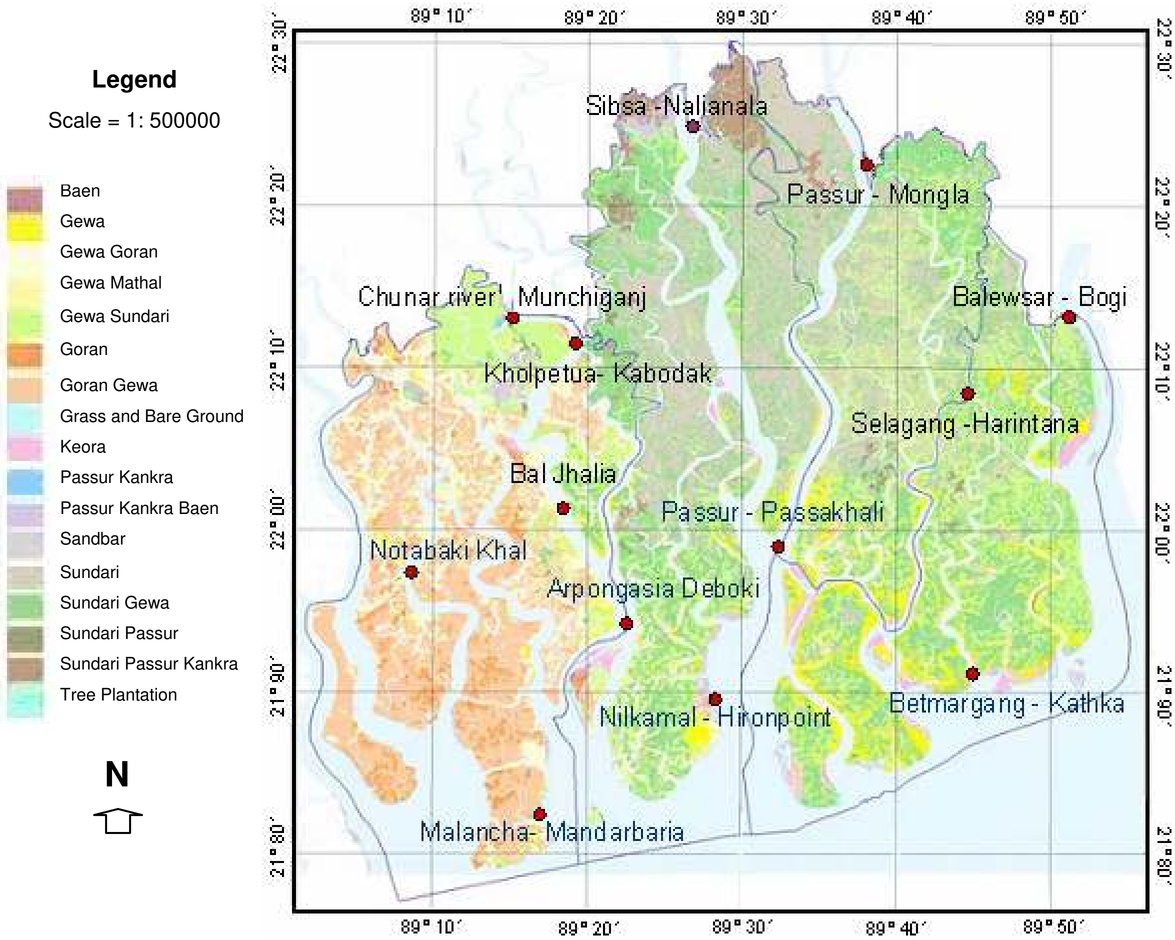


Figure 3.2 The Sundarbans mangrove wetlands location and characteristics

The tidal surges and storms are common in May and October-November and may develop into cyclones, usually accompanied by tidal waves of up to 7.5 m high (Seidenstiker and Hai, 1983; Christensen, 1984). The Sundarbans land and water is part of the world's largest Ganges delta (80,000 km²) formed from deposited sediments by the three mighty rivers (Seidensticker and Hai, 1983). The Sundarbans delta feature is a complex network of streams and varies considerably in width and depth, intersecting the entire area. Some of the rivers are several kilometres in width (Faizuddin et al., 1999; Khan, 1992; Bala, 1998). The rivers of the Sundarbans are more stable than the main stream of the Ganges. The erosion and accretion balance in the Sundarbans has been estimated to be 146 km² for the period 1960 –1984 (Jabbar, 1992; Siddiqi, 2001; 2002).

Table 3.1 The physical characteristics of three ecological zones in the Sundarbans (after Hossain and Acharya, 1994)

Characteristics	*Miohaline Zone*	*Mesohaline Zone*	*Polyhaline Zone*
Soil texture	Silt clay loam	Silt clay	Silt clay
Soil salinity	1383 - 4149.12 dS/m	4841- 6223.68 dS/m	5532-14349 dS/m
Water salinity	0 -17288 dS/m	17288 -38898 dS/m	38898-54025 dS/m
Soil pH	7.7 - 8.2	6.7 - 8.1	7.7 - 8.2
Inundation per year	75 - 120 times	105 - 135 times	135 - 150 times
Canopy closure	60 - 100 %	40 - 80 %	30 - 70 %
Cultural landscapes	Changing due to tourism development	Tourism, business of fry collection, shrimp cultivation etc	Changing due to salinity and shrimp cultivation
Ecosystems	Changing	Vulnerable	Threatened
Tree height	15 - 20 m	10 - 15 m	3 - 5 m

The Rivers of Bangladesh play an important role in the alternation of floodplains in the coastal region. Silt deposition in the north eastern part of the forest poses a threat to the existence and vigorous growth of mangrove vegetation. The causes of silt deposition a rise of the forest floor and due to irregular flow of tidal water, mangrove regeneration does not take place properly. There is a seasonal variation of tidal height ranging between 3.5 to 5.0 meters, while the mean tidal height is 4.0 metres (Chaffey et al., 1985; Karim, 1988).
The following data presents the fractions represented by forest and other land use types in the Sundarbans;

Table 3.2 The Sundarbans forest and land use types (after SBCP, 2000)

Types of Sundarbans lands	*Area km²*	*%*
Forest area	3997	66
Sandbars, grass, background	125	2
Sundarbans reserve forest 1397 km² represented by 3 wildlife sanctuaries	1905	32
Total	6017	100

The climatic situation in the Sundarbans region favours mangrove vegetation in the Ganges delta. In general the climate of the Sundarbans is humid. The rainfall is heavy (2900 mm) and the humidity is high (80 %) due to the proximity of the Bay of Bengal. There are six months of dry season during which evapotranspiration exceeds precipitation. As a result the most saline occurs in February-June, the depletion of soil moisture being coupled with reduced freshwater flow from upstream. The tidal inundation regulates the hydrology of the coastal mangrove area. The hydrology is related to high seasonal rainfall and the duration of the tidal inundation. Seidnesticker and Hai (1983) divided the Sundarbans into four hydrological zones which are based on the frequency of the tidal inundation during the period May to October.

i) Areas inundated by all tides; poorly oxygenated new accretions occupying the months of the big rivers and along the sea coast.

ii) Areas inundated by normal high tides; this zone includes the major portion of the Sundarbans.

iii) Areas inundated only by spring high tides; this zone includes the northern part of Sundarbans.

iv) The areas inundated by the monsoon high tides; this zone is located in the north east part of the Sundarbans.

3.1.2 The geological history of the Sundarbans mangroves

The Sundarbans mangrove is a tropical forest and the geological history of tropical forests are often recognised with the help of bioclimatology. Therefore plants and vegetation remain focal indicators of climatic conditions. The last glacial period occurred some 11000 years ago. So it is confirmed that no part of Bengal basin experienced glaciations during the quaternary period where the temperature was almost 6° C (Tomlinson, 1986; Saha et al., 2001). The lower Ganges delta was under sea around 6000-7000 years ago. As a result of that there was a rapid trend of deforestation by human habitation which caused the shifting of mangrove vegetation from north to south. Considering this statement the Sundarbans mangrove in Bangladesh originated at least 5300 to 7000 years ago, which is a relatively short age compared with global age of mangrove (Saha et al., 2001). On the other hand Bandyopadhya (1968), Alim (1984) and Siddiqi (2001) have given the statement that the Sundarbans was created by the gradual deposition of silt carried by the Ganges from the Himalayas which is not much older than 7000 years. According to Saha (2001) the modern mangrove taxa can be of appreciable geological age which is also mentioned by Muller (1981). According to Islam (2001) about 9000 to 8000 yrs BP, the mangrove possibly existed in the Jessore, Narail, Jhenaidha and Magura and the northern part of Calcutta city. During 8000 to 7000 yrs BP the mangal belt migrated southwards and vegetation covered most part of Narail, Jessore, north part of Satkhira and the part of

Calcutta. Between 7000 to 5000 yrs BP the coastal belt of Bangladesh region covered the Gopalganj and Madaripur districts and northern part of Khulna and Satkhira district. Gupta (1981) also reported that the northern limit of the present day Sundarbans was established at 3000 yrs BP. The Sundarbans mangroves grow on soil formations of recent origin consisting of alluvium washed down from the Himalayas. The surface geology consists entirely of quaternary sediments, sand and silt, intercalated with marine salt and clay (Umitsu, 1997; Islam, 2001). The geological and tectonic relations of the Sundarbans can be traced to the common genesis of the whole of the deltaic plain of the Bengal basin which is surrounded by the Cenozoic Indo-Burman ranges in the east, the Pre-Cambrian Indian shield on the west and the Shillong plateau on the north-east (Rob, 1997).

3.2 The Sundarbans flora, fauna and vegetation dynamics

The mangrove of Sundarbans is unique when compared to non-deltaic coastal mangrove forest. The Rhizophoraceae are of only minor importance and the dominant species are Sundari- *Heritiera fomes*, from which Sundarbans takes its name, and Gewa - *Excoecaria agallocha.* The only reason for this difference is the large fresh water influence in the north-eastern part and the elevated level of the ground surface. There are four categories of forest; low salinity mangrove forests, tree mangrove forests, salt water mangrove forests, and fresh water *Heritiera* forests. The *Heritiera fomes* trees dominate the Chandpai Range at its northern end. The remaining area is a mixture of *Heritiera fomes* and *Excoecaria agallocha*. Virtually the entire Sarankhola Range is covered by mixed *Heritiera fomes* and *Excoecaria agallocha*. Plants species like *Excoecaria agallocha* grows at the peripheral region and the *Heritiera fomes* in the inner part of each forest cluster. *Heritiera fomes* dominate most of the area from north to south of the Khulna range (EGIS, 2000). The western part of the Sundarbans which coincides with the salt-water zone, supports species like *Ecoecaria agallocha,* a dense undestroy of *Ceriops decendra* and dense patches of Hantal palm *Phoenix paludosa* on drier soil. *Xylocarpus* and *Bruguiera* occur sporadically throughout the area. Species like *Heritiera fomes and Excoecaria agallocha* cover most part of the Sundarbans but *Oryza coarctta, Nypa fruticans and Imperata cylindrica* are preferred on mud flats and *Sonneratia apetala* are found on newly accreted mudbanks (Figure 3.3) (Khan, 1986; Salter, 1987). The Sundarbans can be classified as moist tropical forest comprising a mosaic of beach forest and tidal forest (Champion, 1965). The vegetation in the Sundarbans has been classified into three categories concerning salinity tolerance of mangrove species. Fresh water-loving species with narrow ecological amplitude (*Heritiera fomes, Bruguiera species*); The map of the eastern part of the Sundarbans (Figure 3.3) shows that the water and soil salinity level is lower than in the other two western parts.

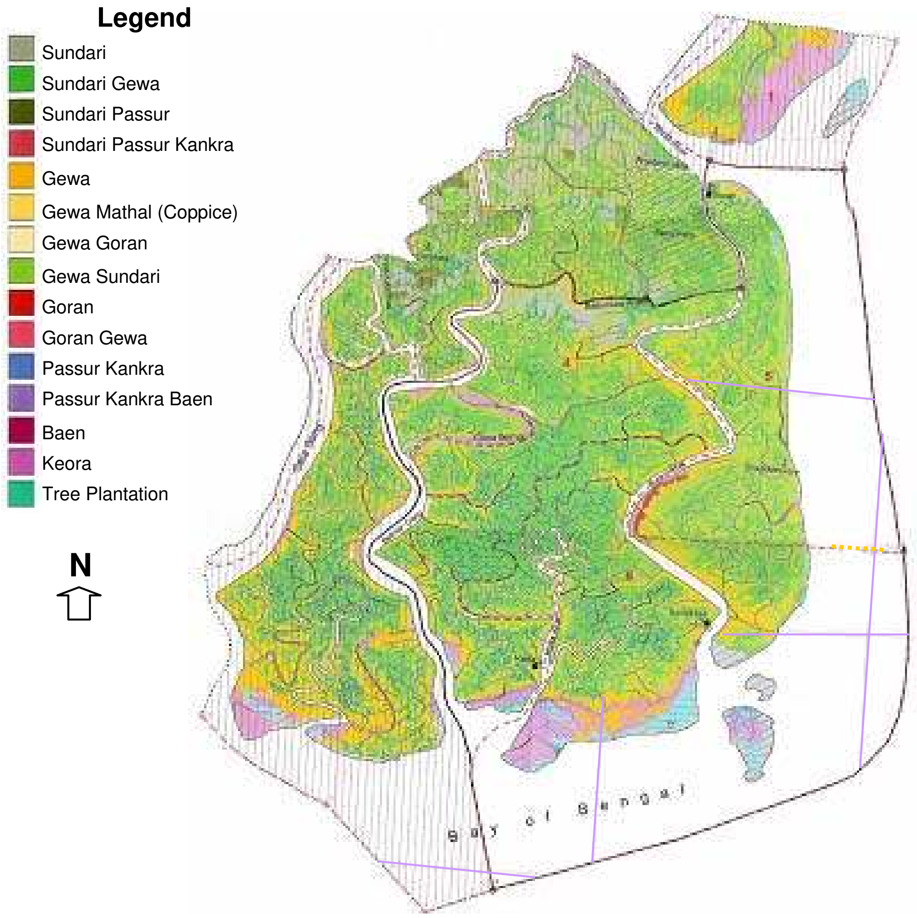


Figure 3.3 The eastern part wildlife sanctuary with less saline water. Source: BARCIK, 2003

The vegetation succession is stronger than in other parts. Moderate saline water tolerating species with wide ecological amplitude (*Excoecaria agallocha, Cariops decandra, Sonneratia apetala, Xylocarpus species*) and saline water loving species with narrow ecological amplitude (*Avicennia species, Agialistis rotundifolia, Rrhizophora apicultura)* (Karim, 1995). The Sundarbans can be classified as moist tropical forest comprising a mosaic of beach forest and tidal forest (Champion, 1965). The vegetation in the Sundarbans have been classified into three categories concerning on salinity tolerancy of mangrove species. Fresh water loving species with narrow ecological amplitude (*Heritiera fomes, Bruguiera species*); Moderate saline water tolerating species with wide ecological amplitude (*Excoecaria agallocha, Cariops decandra, Sonneratia apetala, Xylocarpus* species) and saline water loving species with narrow ecological amplitude (*Avicennia species, Agialistis rotundifolia, Rrhizophora apicultura*) (Karim, 1995). The map (Figure

3.4) shows the middle southern part of the Sundarbans where the salinity level is the moderate level. The vegetation succession and the deltaic landscapes pattern are different from the eastern part.

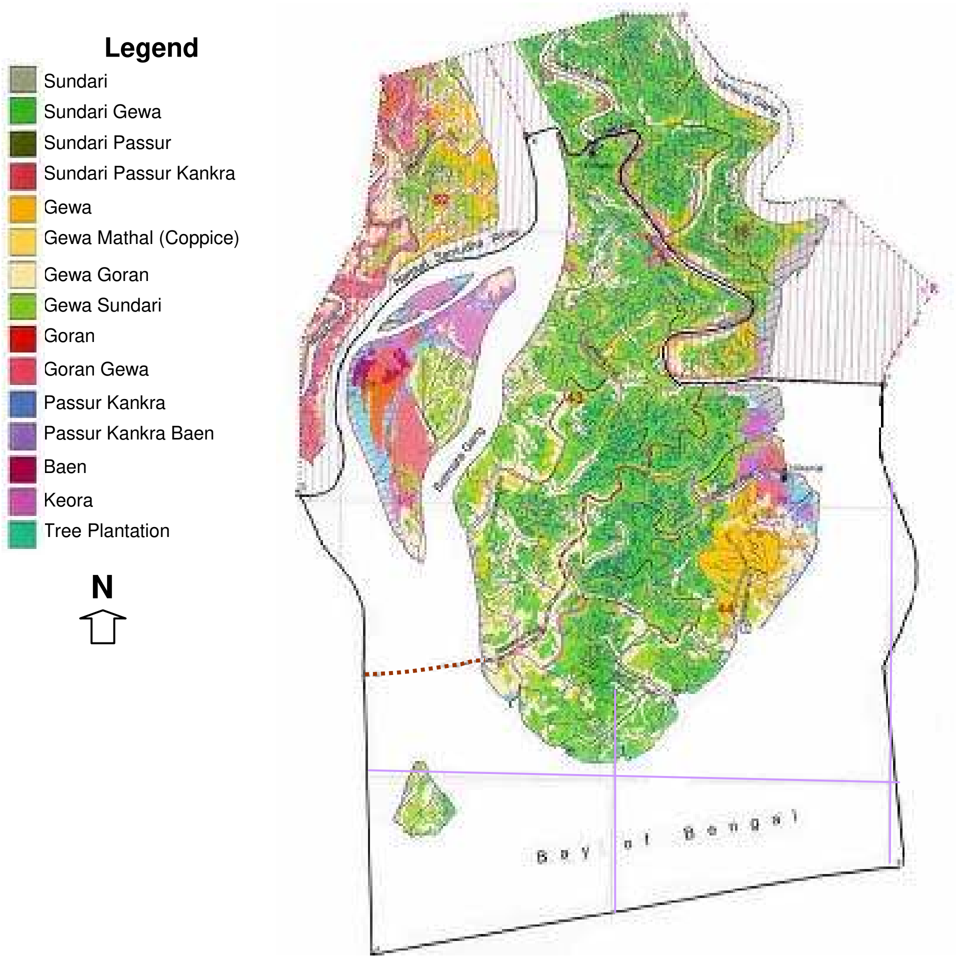


Figure 3.4 The middle part wildlife sanctuary with moderate salinity. Source: BARCIK, 2003

The lower part of these ranges is composed of *Heritiera fomes* and *Excoecaria agallocha*. The north eastern part of the Burigualini range under Shatkhira district is mainly *Excoecaria agallocha* but goran species (*Ceriops decandra)* dominates the remaining area. There are different types of species available in the surroundings of the Saronkhola Ranges and the northernmost part of the Khulna range (EGIS, 2000). The western part of the Sundarbans (Figure 3.5) has been recognised as highly saline zone. The salinity is one of the vital factors in the Sundarbans mangroves wetlands that is controlling the growth and succession of mangrove plants, its height, survival, distribution and species composition of plants in the mangroves. Higher concentration of salt affects plant growth by accumulation of ions in toxic concentration with the plant tissue. Increased salinity not only affects plant association but it impacts on productivity. Timber productivity has reduced with increased water and soil salinity rate in the middle and western part of the Sundarbans (EGIS, 2000). The vast ecological research has been done by EGIS in 2000 and the report has mentioned very clearly that there is a strong relationship between salinity and timber production. Although some mangrove researchers gave their statements that there is no relation to growth of mangroves plants with salinity increase.

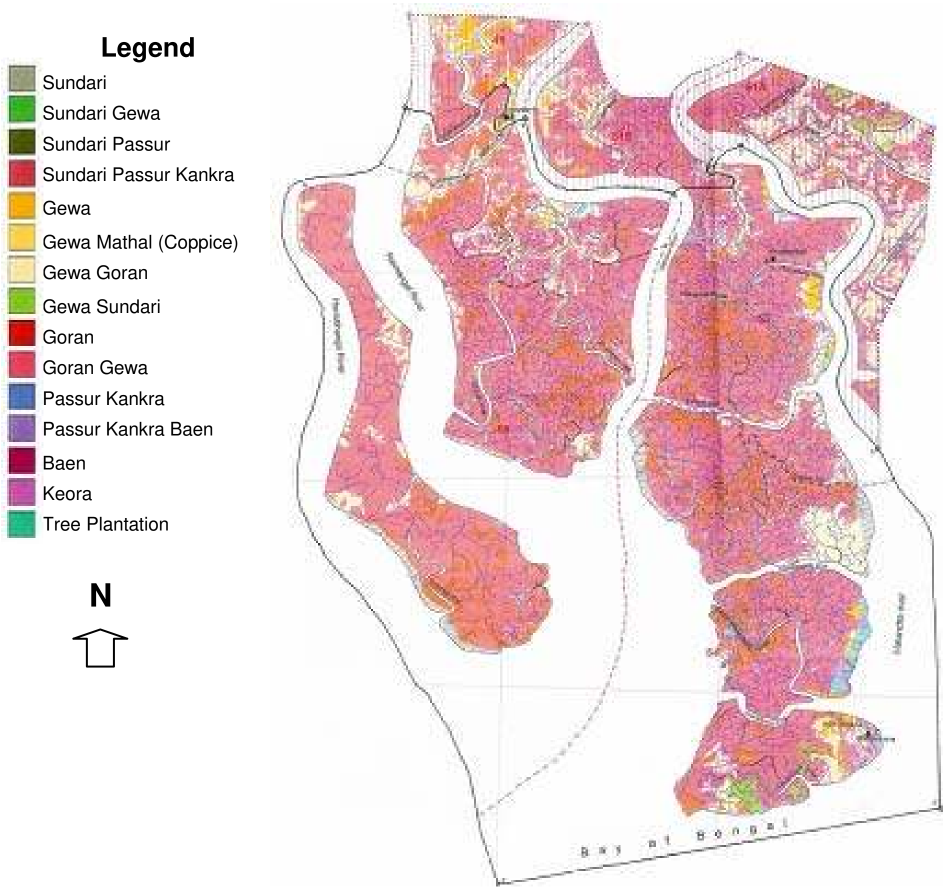


Figure 3.5 The western wildlife sanctuary in high saline zone. Source: BARCIK, 2003

This statement is not proven because it is still subject to application and investigation (EGIS, 2000). On an average 10805 dS/m to 21610 dS/m salinity is the best productive range that means this range could not cross the threshold value of mangrove production in the Sundarbans case (EGIS, 2000). The salinity range 21610 dS/m to 32415 dS/m can be treated as average production level. But above 32415 dS/m the production drops to very low. On the base line condition only 20 % of area is within 32415 dS/m range of salinity. The major part of the Sundarbans mangrove is above 32415 dS/m range where the low production, regretted growth rate, lowers percentage of plant succession and density. On the flip side, this has given way to an increasing number of salt resistant plant species to replace others *Heritiera fomes*, which is the most single dominant and important species of the Sundarbans. Marginal vegetation of the Sundarbans ecosystems are much diversified.

The composition of the common marginal vegetation types are found throughout the forest. There are 5 factors are dominated the vegetation dynamic process (Figure 3.7). The diagramme (Figure 3.6) shows the vegetation composition including Sundari (*Heritiera fomes*-21%), Sundari-Gewa (*Heritiera fomes-Excoecaria agallocha*-29%), Sundari-Passur (*Heritiera fomes -X. mekongensis*-1%), and Sundari-Passur-keora *(Heritiera fomes- X. mekongesis - Sonneratia apetala*-2%), Gewa (*Excoecaria agallocha*-5%), Gewa-Sundari (*E.agallocha-H.fomes*-15%), Goran - Gewa (*Ceriops decandra-E. agallocha*-14%), Gewa-Goran (*E. agallocha-C. decandra*-9%), keora (*Sonneratia apetala*-1%), Goran (*Ceriops deceandra*-2%), and others 1% only.

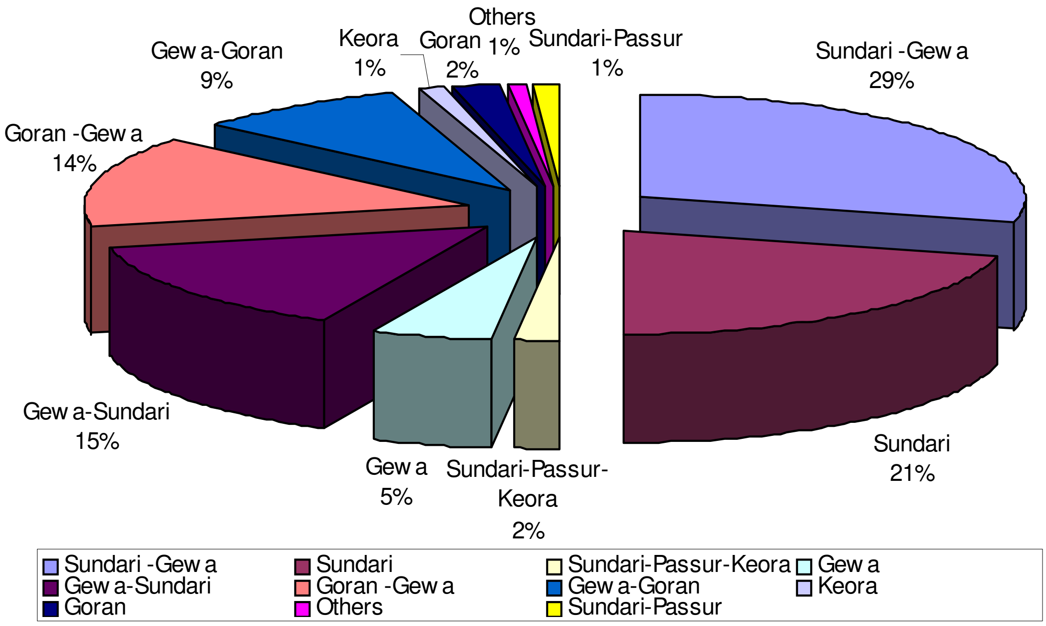


Figure 3.6 Vegetation compositions in the Sundarbans (Data source: Chaffey et al., 1995; Hossain and Acharya, 1994)

As single species *Heritiera fomes covers* 52.7 % of the area and constitutes about 63.8% of the standing volume and a huge percentage is covered by the *Nypa frutican* plants (Rahman, 2001). As pure crop and in mixture with *Excoecaria agallocha*, *Heritiera fomes* occupy about 18.2 % and 62.4 % of the Sundarbans respectively. On the other hand it is recognised that the general composition of the mangrove vegetation of the forest in the Figure 3.6 shows the dominating mangrove species such as *Heritiera fomes* which includes 73 % and 16 % of *Excoecaria agallocha*, *Nypa fruticans* while the rest of all other species together make only 11 % (Faizuddin et al., 1999). Vegetation succession is a fundamental concept in ecology. The vegetation dynamics has many causes. The biological causes can be cast in terms of conditional for example if a certain condition holds then a certain result will follow (Pickett and Mary, 2005). In the case of the Sundarbans the mangrove vegetation dynamics are also changeable. The changing causes are deeply related to these 4 vital factors (Figure 3.7) which are dominating the vegetation dynamics process in the Sundarbans region.

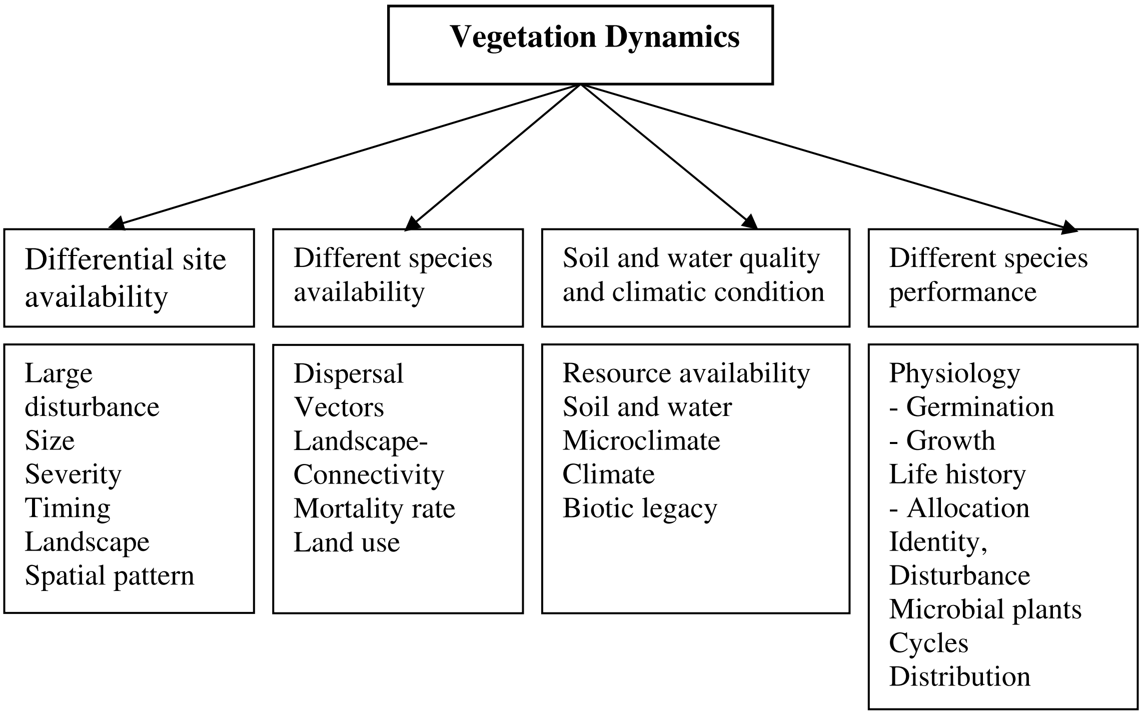


Figure 3.7 The causes of vegetation dynamics (after Pickett, 1989)

According to Forestal (1960) the survey was conducted in 1959, the result stated that the dominant Heritiera forest type is decreasing on a certain scale. The Heritiera forest type was covered to be 31.6 % in 1960, whereas it was found to be 20.0% in 1985 by ODA survey result in 1995 and it further reduced to only 18.2 % by RIMS survey result in 1995. Considering these three survey results, it has been estimated that the reduction rate is 0.38 % per year. At this rate, the Heritiera forest type would disappear within the next 47 years (Iftekhar and Islam, 2002).

Vegetation succession in three ecological zones in the Sundarbans

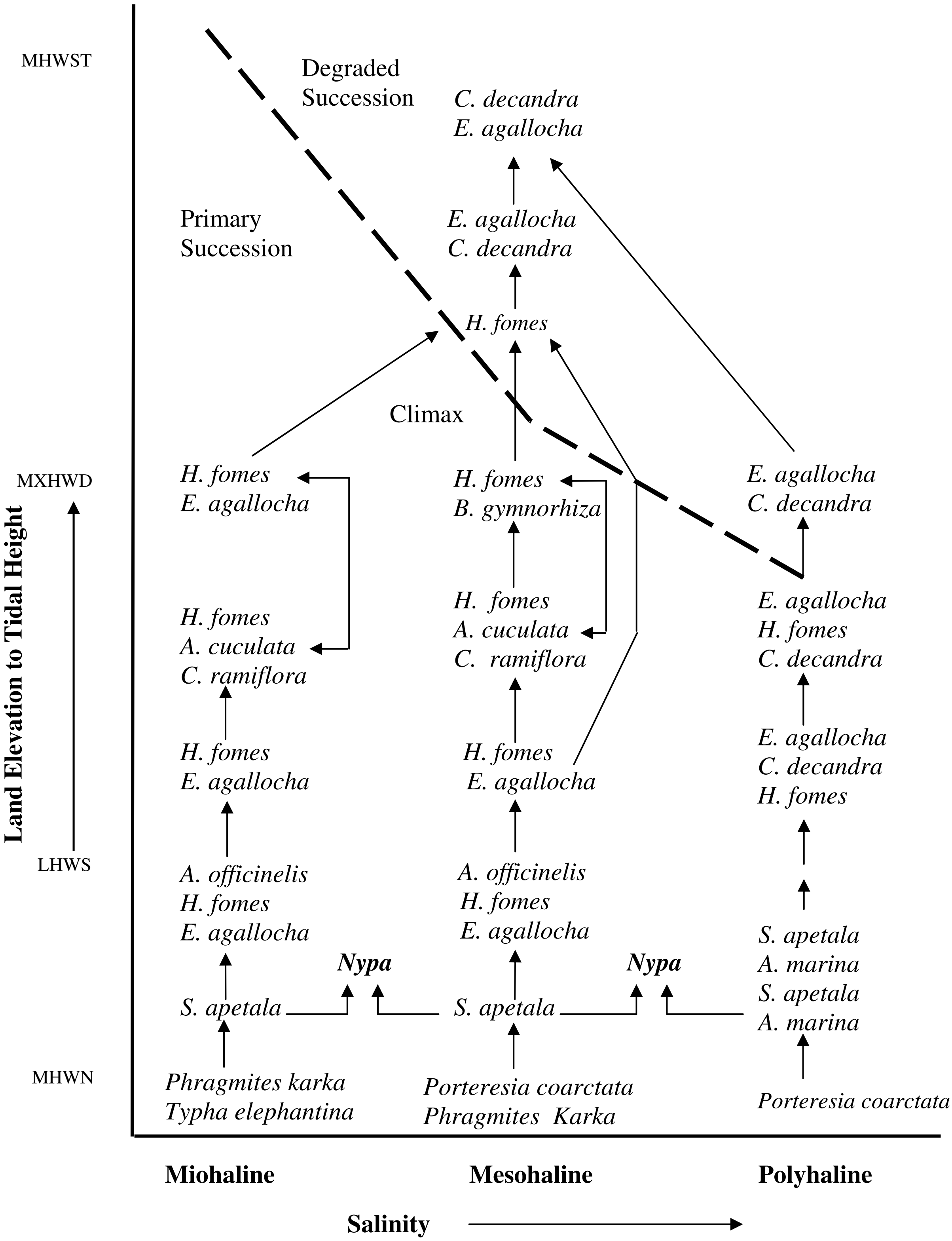


Figure 3.8 The vegetation succession (after Hussain and Acharya, 1994; Karim, 1994)

(Special note: MHWS - Mean high water of spring tides; MHXWD - Maximum high water of spring tides during dry season; LHWS - Low high water of spring tide during dry season; and MHWN - Mean high water of neap tides).

The other two forest types (*Heritiera- Xylocarpus-Bruguiera and Excoecaria-Ceriops*) are also diminishing but at a very slow rate. The Sundarbans is however of significant importance for many species that currently have populations elsewhere, but are likely to disappear in these other sites within the next few decades (Gonzalo, 1998). The plants species of the Sundarbans mangroves wetland is not made up of one homogenous specie group it has a unique heterogeneity combination of different species. The flora of the Sundarbans was thoroughly explored by Heining (1992) as mentioned by Das (1980). Heining (1992) reported 70 species from 34 families, whereas Chaffey and Sandom (1985) enlisted 66 species in the Sundarbans (Appendix - 2).

3.2.1 The faunal diversity

The Sundarbans is the only remaining habitat in the lower Bengal Basin for a variety of faunal species. With regard to wildlife, the Sundarbans possesses a rich faunal diversity even after disappearance of a good number of interesting species (Table 3.3 and Appendix-4). With regard to mammals, birds, reptiles and the amphibians, the Sundarbans shares 45, 42, 46 and 36 percent with the rest to the country. However, seven species have become extinct in the beginning of the last century. Besides, 10 species of mammals, 11 species of birds, 16 species of reptiles and one species of amphibian is endangered (Siddiqi, 2001). They include Royal Bengal Tiger (*Panthera tigers*), Jungle Cat (*Felis chaus*), Irrawaddy dolphin (*Orcaella brevirostris*), Blyth's Kingfisher (*Alcedo hercules*), Estuarine Crocodile (*Crocodilus porosus*), Yellows Monitor (*Varanus flavescens*), Rock python (*Python molurus*), Green Frog (*Euphlyctis hexadactylus*) and others (Siddiqi, 2001).

Table 3.3 Status of mammals, birds, reptiles and amphibians in the Sundarbans (after Rashid et al., 1994; Siddiqi, 2001)

Class	*Total number of species in Bangladesh*	*Existing species in Sundarbans (No)*	*Sundarbans share with Bangladesh (%)*	*Extinct species (No)*	*Endangered species (No)*
Mammalia	110	49	45	4	10
Aves	628	261	42	2	11
Reptilia	109	50	46	1	16
Amphibian	22	8	36	-	2

At present 49 mammals species have been recognised, and of these no less than eight spectacular species, namely Javan rhinoceros (*Rhonoceros sondaicus*), Single horned rhinoceros (*Rhinoceros unicornis*) Water buffalo (*Bubalus bubalis*), Swamp deer (*Cervus* *duvauceli*), Mugger crocodile (*Crocodylus palustris*), Gaur (*Bos frontalis*) and Hog deer (*Axis porcinus*) have become extirpated in the Sundarbans since the last century (Salter, 1987; Sarker, 1992). Generally, the wildlife population of the Sundarbans is under stressed that is why evaluation and better wildlife management strategies are needed as soon as possible and should be immediately implemented for the protection of natural heritage and the ecosystem. The terrestrial type of animals is available for its suitable periodic inundation environment. The river terrapin (*Betagur baska*), Indian flap-shelled turtle (*Lissemys punctata*), Peacock soft-shelled turtle (*Trionyx hurum*), yellow monitor (*Varanus flavescens*), water monitor (*Varanus salvator*), Indian Python (*Python molurus*) and the Bengal tiger (*Panthera tigris trigis*) are some of the resident species.

3.2.2 Mangrove forest type and classification

A mangrove forest is a vegetation unit having characteristics in physiognomy and structure sufficiently pronounced to permit its differentiation from other such units. The Sundarbans mangroves forest has been divided into 13 main floristic types of forest and four non forest types which were investigated by ODA in 1985. The *Heritiera fomes - Excoecaria agallocha* and Heritiera forest types are the most common plants species which cover 50 % of the area. On the other hand according to Das and Siddiqi (2000), economically important plants of the Sundarbans are *Heritiera fomes* which account for 73 % while *Excoecaria agallocha* also account for 16 % and other species such as *Xylocarpus mekongenesis, Sonneratia apetala, Avicennia officinalis, Bruguiera gymnorrhiza, Ceriops decandra* and *Nypa fruticans* are in the minority and form (11%) of the forest. This particular forest inventory divided the Sundarbans into 11 types (Table 3.4), depending upon the predominant species present at a particular place. The area which is divided into 9 blocks (Table 3.4) exclusive of the mangrove species is available in these blocks and it has been measured in km² of the forest areas. The Sundarbans has been differentiated into 13 main floristic types of forest and four non-forest types (ODA, 1985). The *Heritiera fomes-Excoecaria agallocha* and Heritiera type of forests are the most common species of vegetation covering the Sundarbans. The Table 3.5 shows the quality class of vegetation. The stocking of the mangrove forest area in the present day of the Sundarbans can be reflected in a table showing the number of stems of major species per hectares in different blocks, from the blocks situation we can calculate the total number of trees down to 10 cm diameter at breast height of different species (Table 3.6). Stem number is showing bellow;

Table 3.4 Area of major forest types in blocks km² (after ODA, 1985; Siddiqi; Das, 2000 and Chaffey et al., 1985)

Forest Type	*Area by Block km²*									
	1	2	3	4	5A	5B	6	7	8	All
Heritiera fomes	200	141	22	230	01	192	34	00	00	831
H. fomes –X. agallocha	240	118	257	203	35	112	201	00	00	1164
H. fomes -X.mekongensis	00	05	00	11	02	02	01	00	00	22
H. fomes- X.mekongensis-B. gymnorrhiza	00	00	00	60	00	00	04	00	00	65
X. agallocha	10	13	115	01	10	04	22	17	04	196
X. agallocha –H. fomes	121	116	66	24	109	24	120	01	03	585
X.agallocha –C. decandra	00	13	22	00	55	00	127	113	31	362
C.decandra – X.agallocha	00	03	00	00	50	00	48	203	268	572
Ceriops decandra	00	00	00	00	04	00	07	24	58	93
Sonneratia fomes	01	02	16	03	00	03	06	01	01	33
Others	00	00	01	10	15	01	05	02	01	32
Total Forest	582	411	499	542	281	338	575	361	366	3955

Table 3.5 Forest vegetation quality class in the Sundarbans (after Forestal, 1960)

Quality Class	*Total Area (ha)*	*Percentage*
I	102 607	25
II	93 822	22
III	182 838	45
Immature forest	1 215	1
Non- commercial cover	21 194	5
Char-land	5 020	1
Clear land	198	1

Table 3.6 Species number in blocks with in 10 cm diameter (after ODA, 1985)

Species Type	*Stems / Hectares by Species*									
	1	2	3	4	5A	5B	6	7	8	All
Heritiera fomes	485	452	341	365	67	491	231	16	29	2477
Excoecaria agallocha	278	220	322	126	184	102	197	294	268	1991
Sonneratia apetala	1	2	9	3	1	2	3	2	3	26
Xylocarpus mekongensis, Bruguiera gymnorrhiza and *Avicennia officinalis* etc	14	13	13	84	38	28	16	20	7	233
Total	778	687	685	578	290	623	447	332	307	4727

In the table the important mangroves species show the mean number of stem per ha of the merchantable species d.b.h. 10 cm and above in each block.

3.2.3 Forest canopy classes

The predictable changes in plants and animal communities are referred to as ecological succession. Ecologically succession is essentially driven by those physical and chemical changes that communities make in their environment for subsequent different communities, until the ecosystem reaches a long-term stability with respect to its compassing climate. When climate dictates that grassland will turn into a forest land, the grass must be moved. As for plant succession proceeds from early pioneer stages through developmental stages, habitat changes will result in the loss of certain animal population (Erickson, 1994). The mangrove forest canopy structure in the Sundarbans was remarkable than the other parts of the world mangrove forests. In 1960 where forestall classified 78 % of the forest having a canopy closure of 75 % or more (Figure 3.11). A Forest survey in 1985 by Overseas Development Authority (ODA) of United Kingdom showed that 65 % of the forest has a canopy closure of 70 % or more (Figure 3.9 and Figure 3.12). Figures at the subsequent pages show the distribution of three canopy classes and height classes.

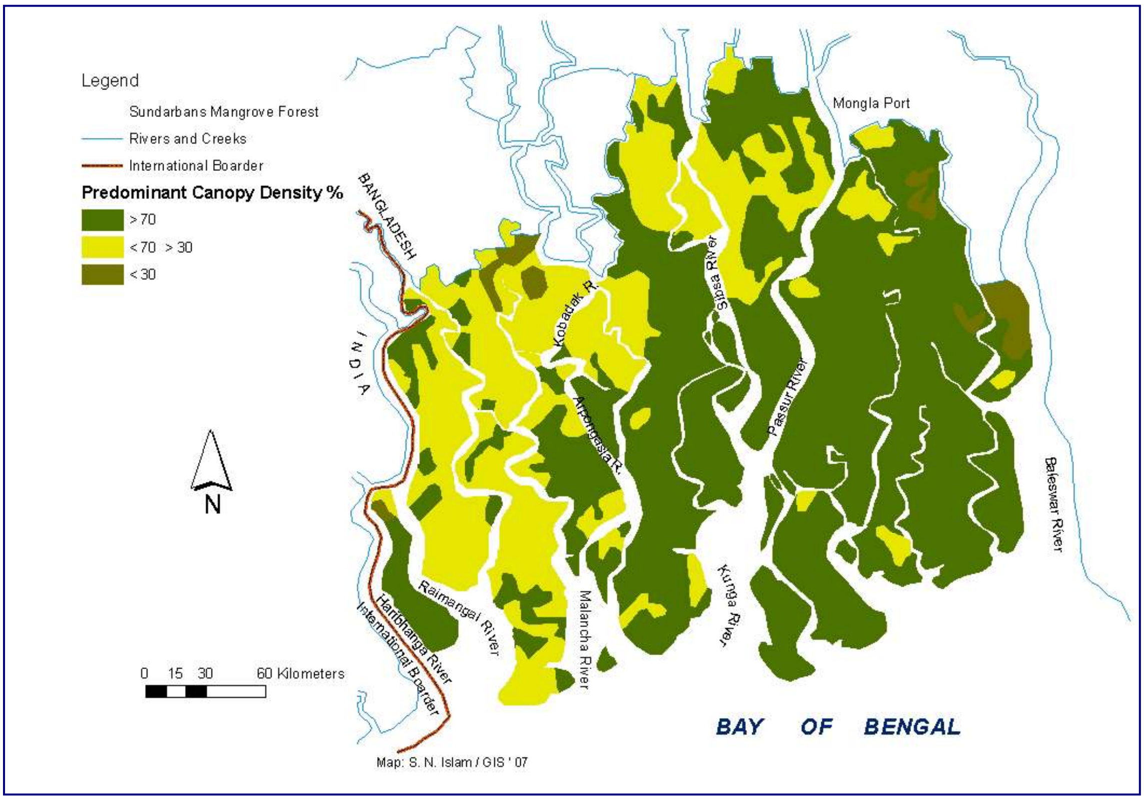


Figure 3.9 Predominant canopy densities in the Sundarbans (Data source: ODA, 1985)

Predominant canopy classes are those having 30 % or more closure and in that the forest is more closed in the east than in the west and the canopy closure in the east. The forest is more closed in the east than west and the canopy closure in the east is more than 70 % in

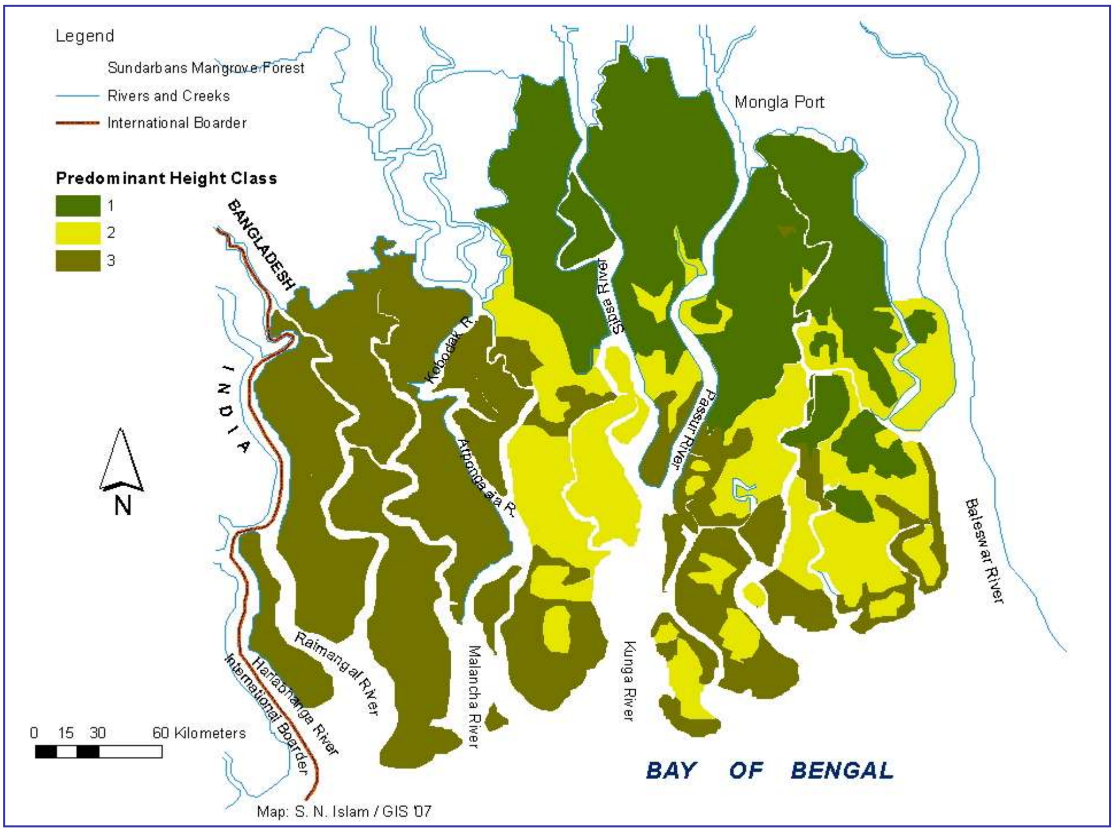


Figure 3.10 Forest Canopy class in 1933 (Data Source: Curtis, 1933)

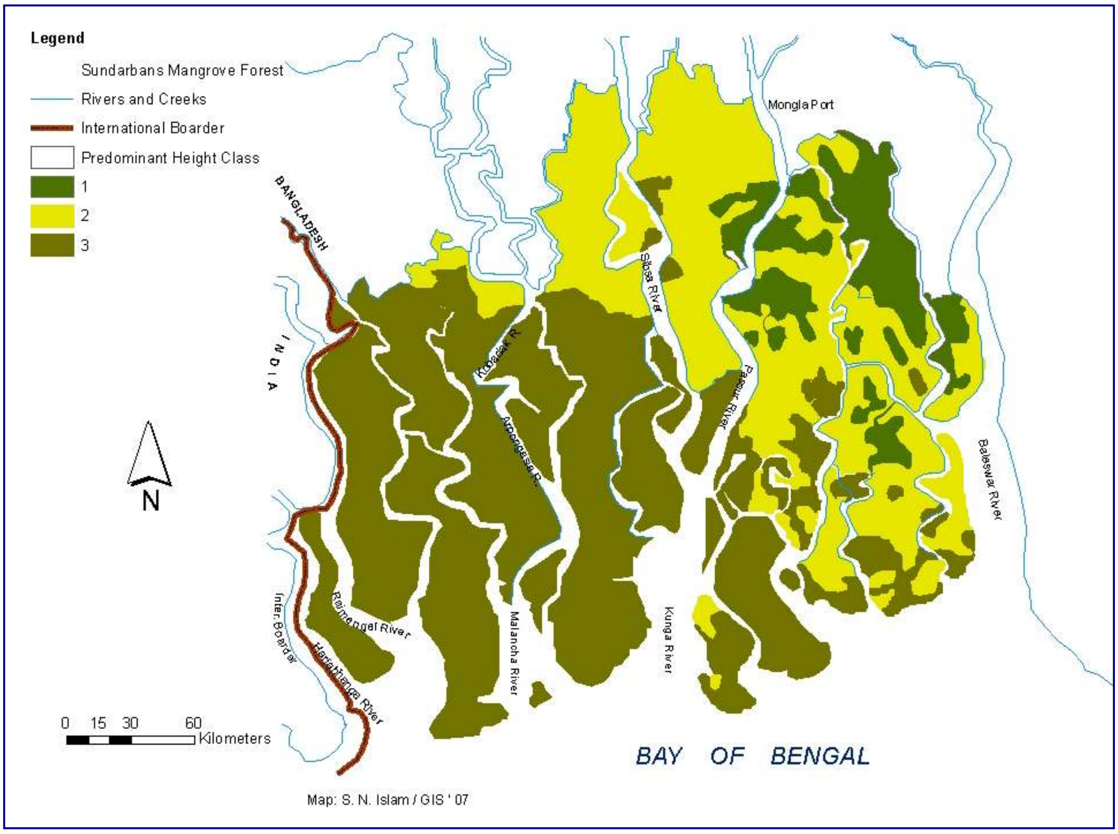


Figure 3.11 Forest canopy class in 1960 (Data Source: Forestal, 1960)

the middle part of the forest which is 30 % and more than 70 % and the western part have 30 % less than 70 % (Figures 3.9, 3.10, 3.11 and 3.12). The Sundarbans forest canopy is seldom 10m above ground level. The major portion of the forest can be categorised into two storied with scattered emergent trees attaining a height of up to 20m. The diameters are generally less than 20 cm at breast height (dbh) in very few cases diameter can be shown up to 1m. The vegetation is in three different height classes such as a) height > 15 m, b) > 10 m, but < 15m and c) > 5m but < 10m.The height of the Sundarbans wetlands mangrove forest is much higher in the east than in the western part of the forest where the salinity rate is lower than in other parts of the forest. The forest height decreases towards the west. It is very clear and understandable that the forest height class is greater where the water and soil salinity is low and the forest height is smaller where the soil and water salinity is higher.

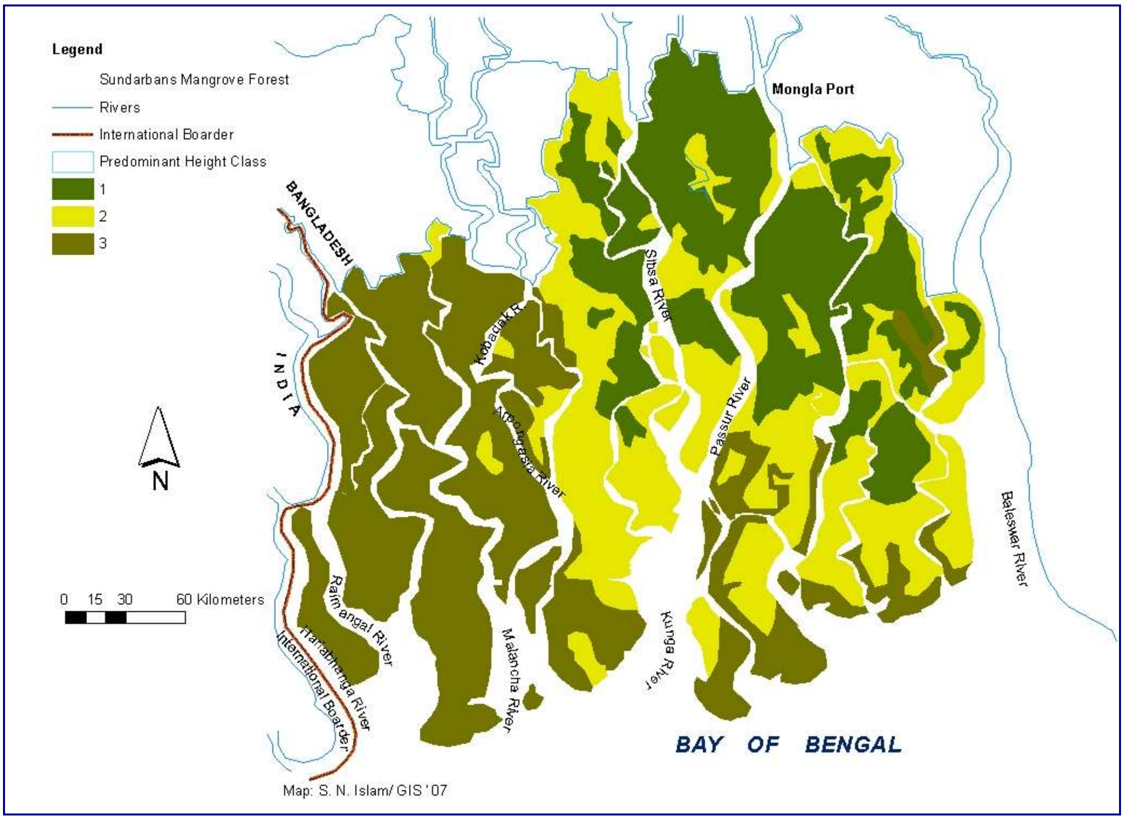


Figure 3.12 Forest canopy height class in 1985 (Data Source: ODA, 1985)

It is an empirical research finding that few trees can be removed from a forest canopy by several kinds of events, as well as wind may snap trees, lighting may destroy the trees, old trees may die and even parasites may kill one species where a mixed species stand and leave a gap in the canopy. In this situation within the gaps the resource availability may be altered and environmental signals may change. In the Sundarbans case of top-dying disease is an example of parasites attacking special tree species like *Heritiera fomes* and other ones. Besides, water may be either more or less available depending on whether the rainfall can better reach the forest floor compared to the rate of soil moisture removal by roots of neighbouring canopy trees and undestroyed plants that remain in the gap. The nutrient like nitrogen can be available in the gap, reason for soil microbes. Soil temperature extremes may increase and soil moisture availability acting germination of demand seeds in forest. As a result, the diversity and productivity of mangrove forest annual plants is greatly enhanced in the deltaic mudflat in the Sundarbans.

3.3 Hydrology and river systems of the Sundarbans

The Sundarbans mangrove wetland is intersected by an elaborate network of rivers, channels and creeks (Chaffey et al., 1985). A complex net of streams and rivers varying considerably width and in depth intersects the entire area. Some of the big rivers are several kilometres in width (Siddiqi, 2001). Rivers tend to be long and straight, also a consequence of the strong tidal forces and the clay and silt deposits which resist erosion. The width of these estuaries sometimes extends to about 10 km. The rivers such as the Passur, Sibsa and Raimangal are deep and wide (Hussain and Acharya, 1994). Generally the rivers flow from north to south and are connected with a large number of side channels. These side channels connect two rivers and facilitate exchange of water between them. The larger rivers, while passing through the Sundarbans forest, join together and form estuaries at the confluence where they meet near the sea (Figure 3.13). The Sundarbans receives large volumes of freshwater from inland rivers flowing from the north and of saline water from the tidal incursions from the sea. The salinity of tidal water is the major force in the productivity of mangrove forest ecosystems. At a comparatively recent period all rivers were connected with the Ganges. The Baleswar River's waterways carry little fresh water as they are cut off from the Ganges; the main outflow has shifted from the Hoogly-Bhagirathi channels in India (Seidenstiker and Hai, 1983).

Currently the Baleswar and Gorai Rivers have direct connection with eastern part of the Sundarbans carrying with them a substantial amount of fresh water to the area (Siddiqi, 2002). These ecological niches occur mainly along the Baleswar, Bhola, Passur, Marjata, Arpongasia, Shibsa, Jamuna and Raimangol Rivers. A number of rivers namely Passur, Sibsa, Selagang, Arpongasia, Kobadak, and Malancha and to a lesser extent Jamuna and Raimangal have indirect connections and receive the overflow of the Ganges during the rainy season. The three sub-systems are based on the hydrological regime of the Sundarbans;

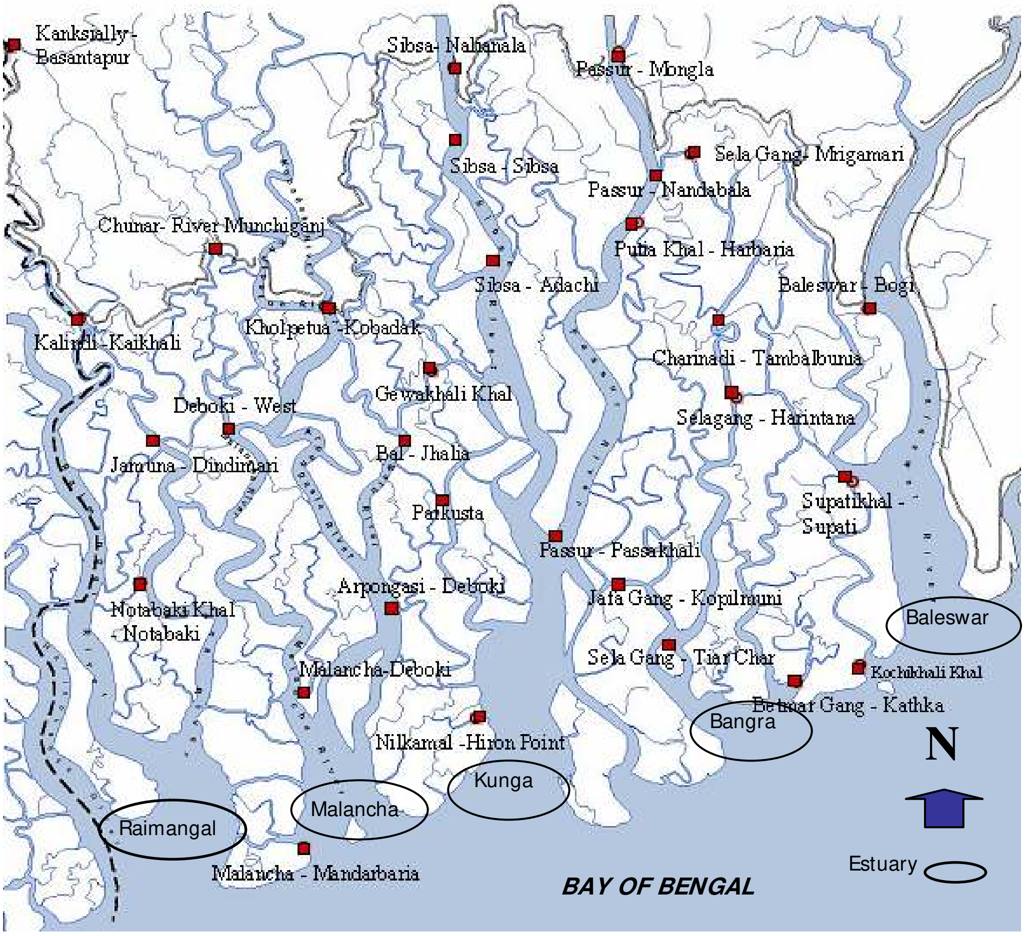


Figure 3.13 Major rivers, river systems and estuaries in the Sundarbans

i) Western sub-system

This area represents the western part of Aura Sibsa and the east of the Raimangal River is connected with the part of upstream moribund delta of Kobadak-Betna River system.

ii) Central sub-system

It is located east of Aura Sibsa and west of the Passur River. It is directly connected with the Ganges through the Gorai River. After constructing the Farakka Barrage the connection between Passur and Gorai has blocked due to settled down of floating particulars and sedimentation.

iii) Eastern sub-system

The eastern subsystem represents the east part of the Passur River and the west part of the Baleswar River. This sub-system receives freshwater from the Ganges through the Gorai-Madumati River. The river systems in the Sundarbans can be divided into 5 estuaries. The estuaries are as follows;

i) Bangra estuary

The Bangra River estuary is found within a large number of tributaries of which Passur, Kanga, Barashiala, Sela gang and Bhola are the prominent ones. A complex network of rivers and channels are connected to these tributaries of the Bangra with Passur in the West and Baleswar in the East. The Sela gang and Bhola River are the two major tributaries which used to carry freshwater from the Ganges through the Bhairab system and Jewdhara and the Dhansagar khal from the Baleswar-Madhumati system at Morelganj (Hussain and Acharya, 1994).

ii) Kunga estuary

The Passur and Sibsa Rivers formed the Mardat River which then flows into the Kunga River. The Kunga flows down and receives the Hansharaj and Kaga near Hiron point. A large number of rivers originated in the catchment areas and which outside of the Sundarbans meet the Passur and Sibsa which drained estuary. Passur has influence on the Bhairab and is connected with Gorai-Madhumati systems through Atarabanki and Nabaganga Rivers. The Gorai-Madhumati is the major spill river of the Ganges and carries out 12 % of flow of the Ganges (Hussain and Acharya, 1994).

iii) Malancha estuary

Before entering the Sundarbans, the Malancha River known as Chunar River joins up with Ichamati River before entering into the Sundarbans forest near the Kadamtala station. Malancha and Jamuna are connected through the Firingi River. The Kobadak and Kolpetua Rivers are connected with the Arpongachia and the Bal River. The Bal and the Arpongachia Rivers join the Malancha River further downstream.

iv) Raimangal estuary

The Kalindi River is used as an international boundary between India and Bangladesh and is renamed as Raimangal towards the south when it flows inside the Sundarbans. Jamuna originates from Kishenganj in India, bifurcates at Bangsipur where it is called Madargang near the north of the Sundarbans (Hussain and Acharya, 1994).

v) Baleswar estuary

The Baleswar River is one of the major rivers in the Sundarbans region. The Gorai River flows from the Ganges in the downstream after Bardia point. It is named Madhumati River which is flowing at the east boarder of the Sundarbans. At present only the Baleswar River carrys fresh water from upstream through the Gorai-Madhumati Rivers and from the lower Meghna River and flows into the eastern part of the Sundarbans.

3.3.1 The Source of freshwater supply into the Sundarbans areas

The sources of fresh water in the Sundarbans region are upstream rivers water, surface water ground water and rain water. The quantities of rain water around the region is still satisfying, the annual rain fall is 2700 mm which is the highest density in the south-western part in Bangladesh. There are 430 rivers in the Sundarbans region and some are big rivers, almost two large rivers are connected with the Ganges (Appendix-5). The Gorai River is one of the major tributary of the Ganges which joins the Passur River downstream. The lower part of Gorai is called Madhumati and carrys fresh water to the Baleswar River. Besides these, there are five other rivers carrying various quantities of freshwater into the Sundarbans (Figure 3.13). These are the Kobadak River, Kholpetua River, Passur River, Sibsa River, and Baleswar River. The Kholpetua and Kabadak River receive fresh water mainly from the runoff and the polder areas in addition a proportion of the Gorai inflow. The Passur and Sibsa receive fresh water from Gorai off take, while the Baleswar is fed partially by the Gorai and also from right bank spill channels of the Ganges and Meghna Rivers. This is the only major source now which is carrying upstream fresh water from the Ganges. These 5 major rivers jointly carried between them freshwater of 1175 m^3/sec in 1995 and 1320 m^3/sec in 2001 (IWM, 2003). These small rivers have their sub-catchment area and this area is collecting water from rainfall and from neighbouring big rivers, all the waters are emptied into the Sundarbans.

3.3.2 Transboundary Ganges water withdrawal and salinity intrusion

The Ganges is one of the major transboundary rivers in the South Asia and it plays an important role in the regional economy and floodplain fertility and agricultural production. The Ganges occupies the most important basin in India and Bangladesh. The total length of the Ganges from its sources to its outfall into the sea is 2,525 km. The area of the total basin area is 861,404 km^2 and about 303 million people are settled here in the catchment area. The length of the main channel of the Ganges (Padma) in Bangladesh is only 141 km excluding the common boundary of 112 km. The Ganges basin in Bangladesh contains only 6.1 million acres, and supports a population of over 12 million people (Begum, 1987). The proportion of the Ganges catchment area in Bangladesh is only 7.5 %. Melting snow from the Himalayas also contributes to the perennial flow of the Ganges River but the flow condition is highly subject to the seasonal variation. In the Ganges sub-basin the per capita river flow is 1254 m^3/year and the depth of the flow per hectares of cultivable area is 0.58 m. There is an alteration of landscapes due to the loss of saline-fresh balance when the off take points of Mathabhanga, Kobadak and other rivers bringing fresh water from the Ganges to the southern region were silted up and lost their connection with the Ganges. The Ecological situation became further imbalanced when India constructed the Farakka Barrage in 1975 on the Ganges River, 17 km upstream from the Bangladesh border, and began diverting more then half of water (more than 57 %) (Figure 3.14) to the Hooghly

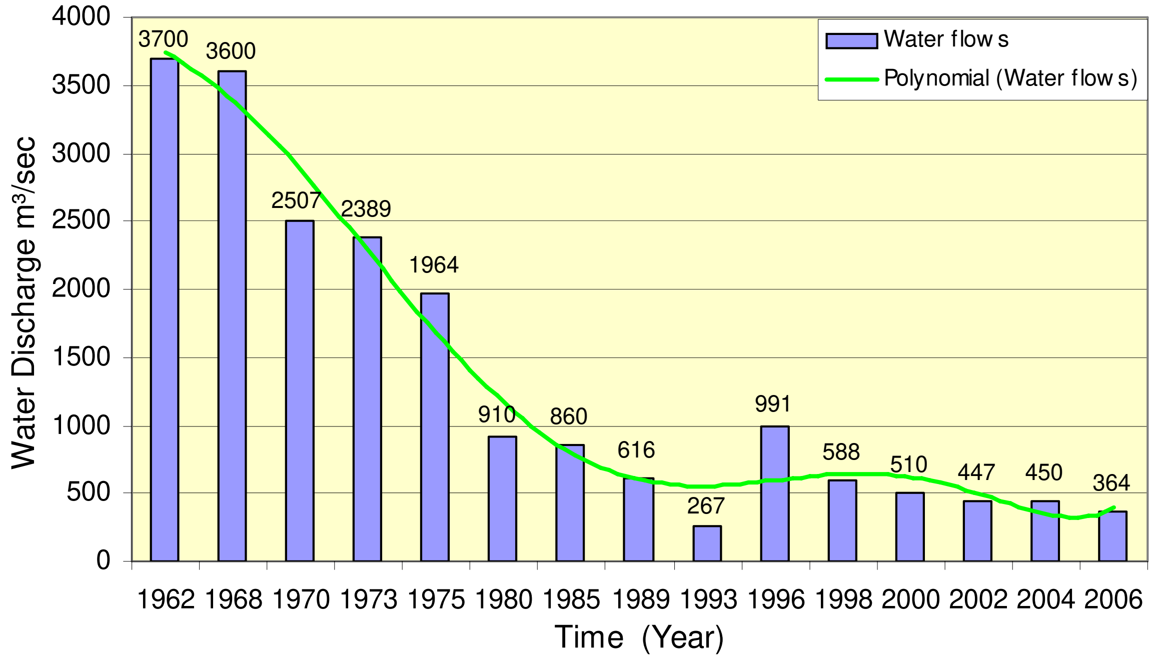


Figure 3.14 Ganges water levels at Hardinge Bridge in the dry season

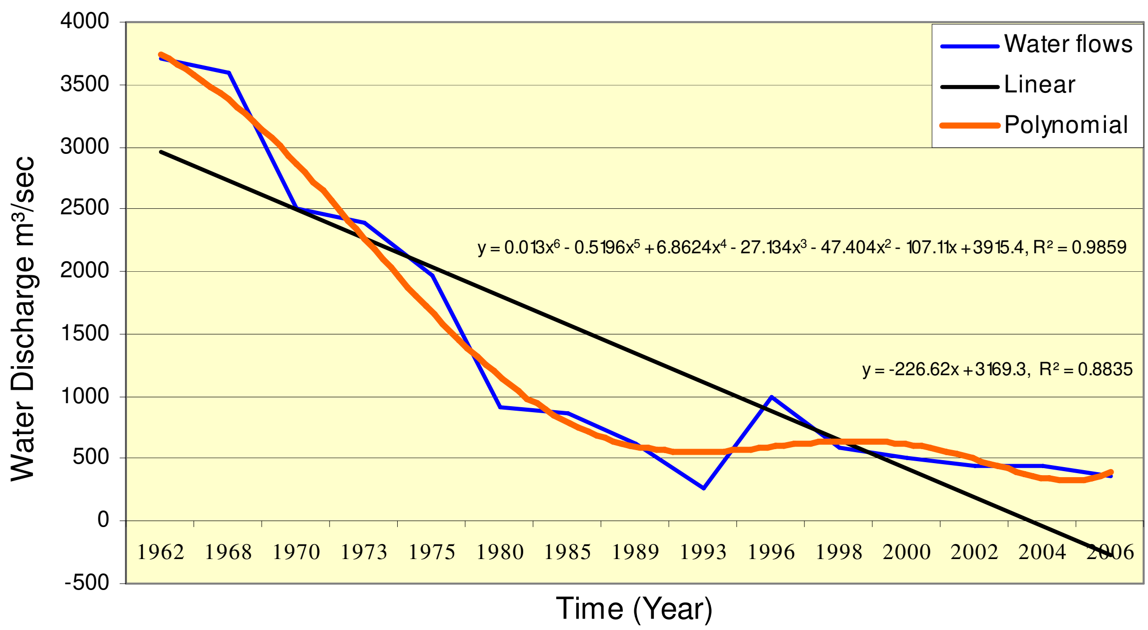


Figure 3.15 The Ganges water flows at Hardinge Bridge during the dry season. (Data: Nishat, 2006; Muniruzzaman, 2001; Jabbar, 1995; Ben, 1995).

River in India. This blocked the perennial flow of the Ganges and diverts its water through a feeder canal into the Bhagirathi-Hoogly River for the improvement of navigation for the Calcutta port (Farzana and Nadia, 2001). Historically the upstream flows was normal for example the Ganges River discharge at Hardinge Bridge in 1962 was 3,700 m^3/sec and in 1968 (Figure 3.14) when the average monthly flow of the Gorai in the dry season exceeded 3,600 m^3 /sec and after this period the flow of Gorai River dropped in 1976 (Ben, 1997; Abbas, 1982).

The Ganges recorded the lowest flow of 267.33 m3/sec on 6 April, 1993 against a flow of 1841.35 m^3/sec as the pre diversion period. In 1995 it was less than 500 m^3/sec and of recent years flows recorded shows a figure of 364 m^3/sec (Figure 3.15) (Khan, 1995; Nishat, 2006). Bangladesh and India have had been having conflicts over the Ganges water resources for about 30 years. These two nations have signed three different treaties within a span of 21 years 1975, 1977 and 1996 about water resources usage of the Ganges after the construction of the Farakka Barrage (Sakamoto et al., 2001; Khan, 1995). These agreements have not been all that smooth, because of different political social perceptions of both countries. Many times these agreements favoured the Indian part considering the supply of water already available in the down stream. Bangladesh is more vulnerable to flood and drought than India by reason of the Farakka Barrage. Both countries have been suffering from a lack of water and unplanned usage. The temporary water sharing treaty was concluded between two countries in 1975 for the first time, this treaty indicated that India draws 310-350 m^3/sec of water from the Farakka Barrage and discharges 1245 -1400 m^3/sec of water to the downstream from April 21 to 30 which happens to the lean period of the year (Farzana and Nadia, 2001; Begum, 1987). The shares of Bangladesh and India based on the flows reaching Farakka at 75% availability are given as follows (Farzana and Nadia, 2001; Ben, 1997). After 1984 there was no rule for the Ganges River water resources utilisation between the two countries and the treaty concluded again in 1996.

Table 3.7 Rules of allocation of water on 1996 Treaty (m^3/sec) (Source: Sakamoto et al., 2001; Khan, 1995)

Availability at Farakka	India	Bangladesh
1,982 less	50 %	50 %
1,982 ~2,124	Balance of flow	991
2,124 more	1,133	Balance of flow

During the time when the total amount of flow is less than 1,982 m^3/sec, India and

Bangladesh draw almost 50% according to the agreement (Table 3.7). A thirty year agreement which was signed in 1996 bought settlement to the dispute of the two countries for the time being, but the conflict does not seem to be completely resolved. The Figure 3.16 shows the salinity increasing trends after Farakka at Passur-Mongla point. The amount of the Ganges water flow in Bangladesh remarkably reduced that has negative environmental effects in the downstream.

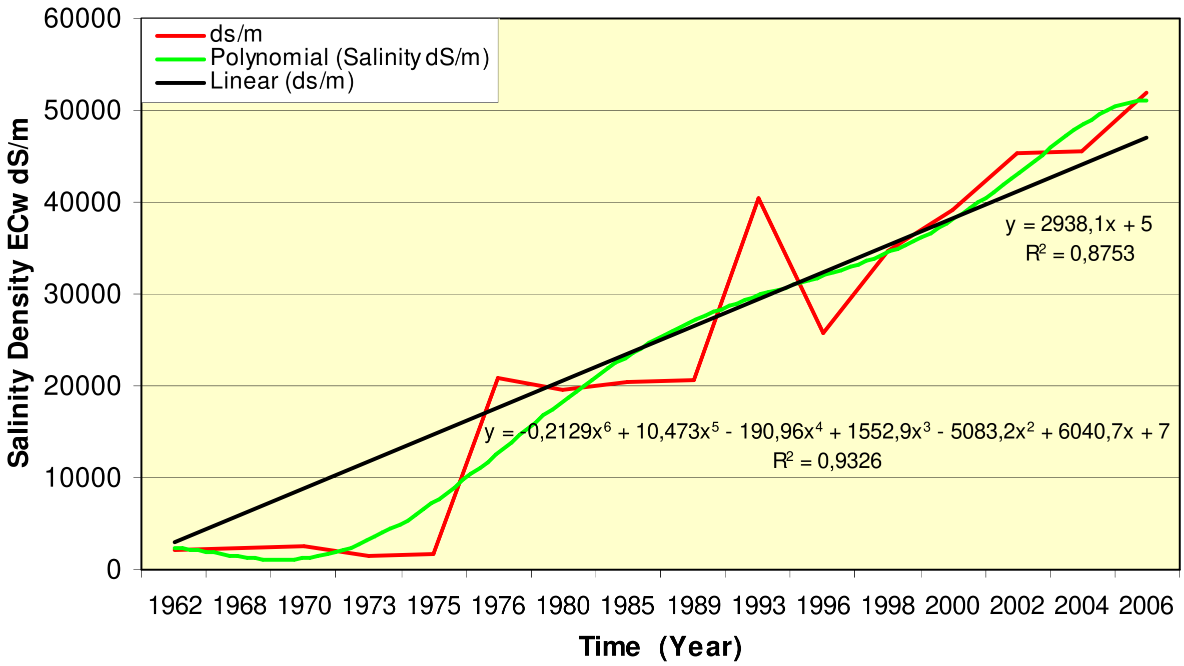


Figure 3.16 The Ganges water scarcity and salinity increase at Passur-Mongla point

The Ganges water flow in 1962 was 3700 m^3/sec whereas it was 364 m^3/sec in 2006. In Figure 3.14 and Figure 3.15 the polynomial model shows the reduction discharge for a long duration and the regression value $R^2 = 0.9859$ is found in the early stage of 1970's when the discharge was greater. On the other hand the regression value $R^2 = 0.8835$ was found in 1980 when water flow rates were already at a reduced level. Accordingly water salinity was increasing (Figure 3.16) simultaneously at Passur-Mongla point, where the regression value $R^2= 0.9326$ was found in 1993 whereas the regression value $R^2= 0.8753$ was found in 1993. Figure 3.16 shows that the salinity trend was normal at Passur-Mongla point (entry point of Sundarbans) until 1975 just before the construction of the Farakka Barrage, and after withdrawal the Ganges fresh water from the basin; as a result water salinity increased from 4322 dS/m to 32415 dS/m, this trend continued until 1988. There was an acute shortage of fresh water in 1993 (Figure 3.14; 3.15) and immediately the salinity rates increased in greater heights. The salinity rates suddenly decreased from 1996-

1998, the reason for that, in 1996 the Gages water sharing agreement had been done between Bangladesh and India. It is an indicative of the fact that the agreement was in place for a short period of time, after this three year duration, water flow gradually reduced again and corresponding salinity levels increased accordingly.

3.3.3 Quality and quantity of freshwater in the Sundarbans rivers

The main sources of freshwater in the Sundarbans forest areas are the major 5 rivers and these rivers are carrying fresh water from upstream. At the upstream the Ganges River is the most important and a huge fresh water supplier to the Sundarbans. The other rivers like Madhumati Baleswar River, Passur River, Sibsa River, Kobadak and Kalindini Rivers play a vital role in the supply of water to the Sundarbans. Historically, these rivers do contribute to the balancing of the ecosystems in the whole region. The excess water flow of the Ganges during the wet season could be stored and potentially used in the dry season. It is estimated that the requirement of Ganges fresh water supply to Sundarbans is 48.49 MAF (Million Acre-Feet) and other rivers like Kobadak and others also supplying similar quantities of surface waters to the Sundarbans (Begum, 1987). It is clear that the upstream rivers surface water does mix with the sea water and makes it difficult to estimate the quantity of river water in the Sundarbans region. The Sundarbans is a vast area and the water body is 2000 km^2 in the form of rivers and creeks. The quality of waters in the Sundarbans mangrove wetland is low considered on high concentration of NaCl in water. The other parameters of water quality have not been considered in my research. In some cases the elective conductivity, pH and organic matters in waters were recognised for consideration of water quality analysis. For considering water quality other parameters like pH, BOD, DO and inorganic components like COD, NH_3-N, PO_4-P and heavy metal like Cr, Pb, Hg etc are important components. Some water qualities tests have been done by the Institute of Water Modelling and results were collected. The Ministry of Environment and Forest (MoEF) defines Environmental Quality Standards (EQS) in Bangladesh. The DOE Gazette has defined the limiting values for only 4 parameters in 1997 such as pH, BOD, DO, total Californ, and inorganic compound, heavy metals like COD, NH_3-N, PO_4-P and Cr, Pb, Hg etc in 1991. Table 3.8 shows the defined limiting values for the parameters of water quality; Some results of water quality parameters were found in IWM investigation in 2003. The maximum BOD concentration occurs in April and the minimum is found in November-December (2001-2003). The overall range was 2-120 mg/L and average range

Table 3.8 Limits of water pollutants (Source: DOE - EQS Report, 1991; 1997; IWM SBCP Report, 2003).

Parameters	**Considerable limit**
BOD	2-10 mg / L
Coliform - total	50-500 nos/ 100 ml
DO	5 - 6 mg /L
pH	6.5 - 8.5
COD	4 - 8 mg /L
NH_4- N	0.025 - 3 mg /L
PO_4 -P	6 -10 mg /L
Hg	0.001 mg /L
Cr	0.05 mg /L
Pb	0.01- 0.2 mg /L
Oil and Grease	0.001-15 mg/L

was 11.3 mg/L which was exceeding the upper limit of EQS. The COD concentration range was found to be from 5 to 255.4 mg/L with an average of 35.96 mg/L it also exceeded the permissible limit of 4-8 mg/L. The DO concentration (2001) was found to be at a very high rate in the east rivers while there was a low concentration in western rivers (2002), DO ranges from 4.90 to 6.90 mg/L with average value of 5.99 mg/L (Table 3.8). The range was within the allowable limit in the marginal condition. The concentration range of NH3-N is found 0.001 to 0.33 mg/L and the average range was 0.043 mg/L but the concentration rate of NH4-N was between 0.040 - 6.74 mg/L and the average value was 2.183 mg/1. The average value of total Ammonia (NH3 + NH4) was found to be 2.2 mg/L and in some places it was found to be even more than 3 mg/L. The pH value of river systems was found to be 7.5; the river water was a little alkine. The PO4-P concentrations were generally found in the low range like 0.009 - 0.582 mg/L and the average value was 0.115 mg/L. The concentration values of heavy metals like Cr, Pb and Hg are higher than the permissible limit 0.05 mg/L, the Pb concentrations exceeded the allowable limit 0.2 mg /L. Oil and Gas concentration value was found to be at the higher value of 0.001 mg/L (Table 3.10). As a whole, the rivers water quality in the Sundarbans region is gradually degrading which is also a threat for ecosystems. NaCl is one of the most important parameter for water quality and water is the key element for ecosystems. Water salinity modelling has been analysed more detailed in the following chapter.

3.3.4 State of salinity of the investigation area

The case area of the Sundarbans is situated in the southwestern part of Bangladesh; the area is bigger than the Netherlands. The area has been affected by the reduced flows of the river Ganges. It is a complex part of the delta of the rivers Ganges, Brahmaputra and Meghna. It is the moribund region of the delta. Many small rivers and canals are no longer, tributaries of the river Ganges; for a long time they had no flowing water only some are active and flowing in the rainy season. There are three sources of water flowing into the south-west region of Bangladesh. The flow of the major rivers coming from India, primarily the rivers Ganges, second, rainfall draining from the surrounding countryside and finally a contribution from water stored in the ground. The Ganges River is the largest source of water flowing across the boarder from India. The Gorai and Arial Khan Rivers are two tributaries draw water from the Ganges in Bangladesh. In the case of the Gorai-Madhumati, the discharge in its upper reaches, the Gorai is influenced by the movement of the channel of the river Ganges near Khustia and the extent to which the off-take of the Gorai is blocked by sand banks. It was reported that at different times a monthly average discharge of less than 30 m^3/sec has been recorded for all months between December and May.

Owing to the high sensitivity of the salinity model the dispersion coefficients for the dry and wet period has made little different scenarios. The density induced contribution to the pressure, gradients increases linearly with the water depth, so the effect is stronger in the deeper rivers, where the density driven flows develop during slack water with a negligible surface slope (IWM, 2003). The investigation area is divided into three ecological zones (Figure 3.17) (Karim, 1995; 1988). These zones are oligohaline where salinity from 0 - 1085 dS/m, mesohaline where salinity from 1085 - 38898 dS/m and polyhaline where salinity > 38898 dS/m. The closed boundaries with consideration of rainfall runoff have been treated as closed in the salinity model. In the southern part of the model areas, all the tidal boundaries have been considered as open, where salinity concentrations have been specified from the observed data. The observed data which has been collected from the influential 13 rivers points out of 29 rivers in the case area has been shown in the investigation area map (Figure 3.17). The surface water flow in the rivers of the Sundarbans area mainly comes from the Ganges-Padma at the off take of Gorai through the Passur River in the Sundarbans and Gorai-Madhumati and from the lower Meghna through the Swarupkati-Kocha River. Few other sources from the local river surface flows from the local catchment areas. Some of the rivers in the catchments area like Bhairab, Bhadra, Chitra, Chunar, Kobadak and Khulpetua among others normally receive runoff water from their own catchment area. Salinity is defined as the amount of dissolved salts present in water. It reflects the dominant forcing functions of freshwater discharge and oceanic exchange. Salinity content of river in Sundarbans shows great spatial variability.

Figure 3.17 State of salinity of the investigation area in the Sundarbans

In the estuaries salinity is an integrated index of mixing process of rainfall, freshwater surface and subsurface flow, tidal water and evaporation. During pre-monsoon (March-May) the conductivity of river water is high and ranges between 9681.28 dS/m to 71918.08 dS/m. In the post monsoon season (August-October) the conductivity of rivers water decreases 0-29735.36 dS/m. These results are found in my study. These seasonal patterns and their spatial variability of river water salinity have been largely attributed to three factors according to Karim (1988),

i) Seasonal precipitation,

ii) Evapotranspiration regime,

iii) The river discharge fluctuation and tidal regime.

Conductivity of saturated soil samples from the north and middle of the Sundarbans regions varies between 898.97 and 12405.86 dS/m. This conductivity is much higher than that of surface soil (Cheffey et al., 1985; Hassan, 1990). In the entire Sundarbans the salinity intrusion has been increasing after upstream freshwater withdrawal. Actually there is no enough in-depth research on the Sundarbans based on particular environmental sectoral issues. The salinity intrusion in the Sundarbans has been shown bellow in a structure format;

Table 3.9 Salinity stress during 2001–2002 inside the Sundarbans (after IWM, 2003)

Duration in days	Percentage of area (%) under different salinity (dS/m) level						
	> 54025 dS/m	43220 – 54025 dS/m	32415- 43220 dS/m	21610- 32415 dS/m	10805- 21610 dS/m	<10805 dS/m	Area %
120	0	25	28	19	15	13	100
90	6	31	28	15	14	6	100
60	6	31	28	15	15	5	100
45	28	30	17	11	10	4	100
30	29	30	17	11	9	4	100
15	29	30	17	11	9	4	100

On the other hand the area covered by salinity and range of salinity which has been showing in the water salinity model investigation areas is not satisfying (Table 3.10).

Table 3.10 Sundarbans area covered by different salinity range (Data source: EGIS, 2000)

Area km²	Salinity dS/m	Percentage of area cover
4813.60	> 32415	80
421.19	21610 -32415	7
421.19	10805 - 21610	7
361.02	< 10805	6

Beside these the overall situation of rivers water salinity in the Sundarbans mangrove forest area has been shown in the graphs below (Figure 3.18). The 13 important river basins have been recognized for their potential role to decrease and increase the salinity at different points. The diversion of upstream waters resulted in falling water table and greater water salinity downstream of Bangladesh especially in the Sundarbans region.

The saline water intrusion was constructed by the upland flows, with a decrease in the upland flows the salinity has increased and advanced for distances inland (Ben et al., 1995). There has been a comparison of the salinity intrusion from 1967- 68 with the situation which occurred during 1976 and 1977 because the unimpaired dry season flows of these years were comparable and better records were available for these years.

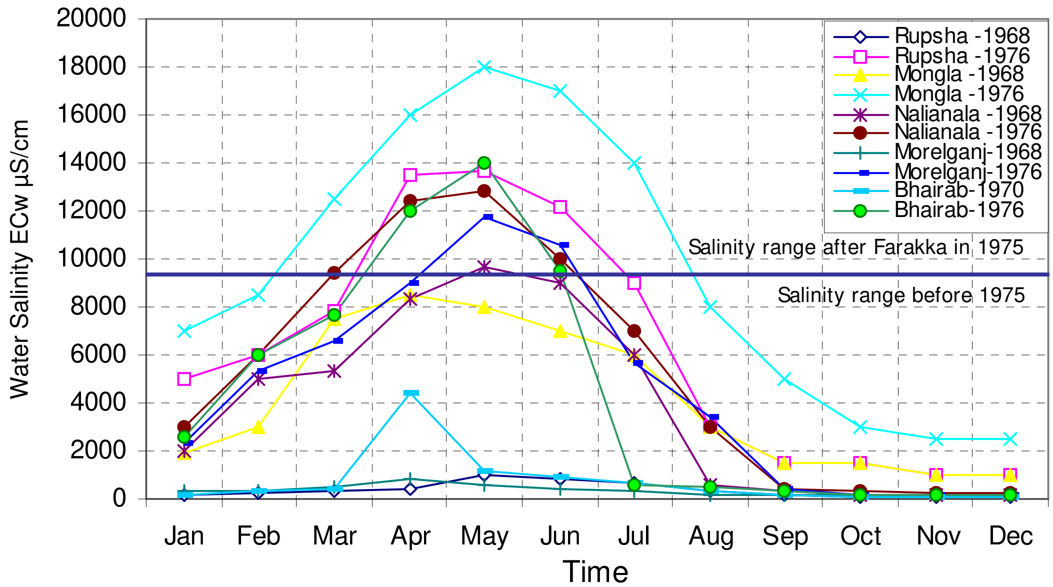


Figure 3.18 Water salinity trends in the Sundarbans region before and after construction of Farakka Barrage 1968-1976. (Data: Khan, 1983; Ansarul, 1995; FAO/UNDP, 1995)

The most dramatic saline intrusion during 1976 and 1977 occurred in the Passur estuary and up the Rupsha-Passur to the Nabaganga, the Atharabanka and the upper Gorai-Madhumati and is connected with the Ganges water withdrawal. Figure 3.18 shows the general trends of salinity in 1968 with 5256 µS/cm registered only 4 miles downstream of Khulna city, the maximum salinity rate in Khulna was about 1383 µS/cm. But when the Gorai River flows dropped in 1976 the high salinity rate moved to Khulna and up to Bardia point (173 km far from the coast). The maximum salinity measured at Khulna in 1976 was about 18809.34 µS/cm in Figure 3.18. The salinity intrusion has been gradually increasing in every dry season. However, the estuaries intermixing pattern of river salinity is very complex. The rise and fall of salinity in all the rivers does not take place simultaneously. The salinity situation in the Sundarbans investigation area has been done considering the salinity increasing trends in the period 1968 to 1976. The figure (Figure 3.18) shows the different salinity increasing and decreasing situation at the potential places and rivers in this area. They are influenced by salinity increasing processes. A general survey was conducted on water and soil salinity of the Sundarbans in 2003 (Figure 3.19). The findings show that the soil salinity is increasing slightly from east to west and from north to south.

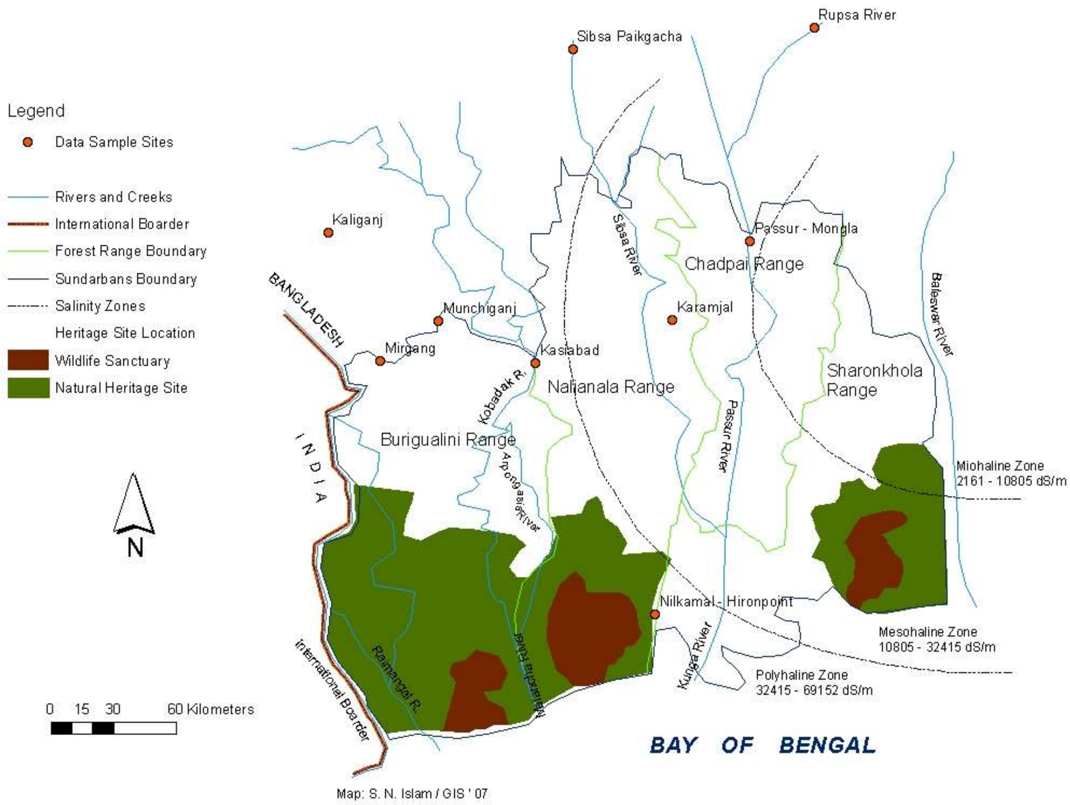


Figure 3.19 The location of salinity samples in the Sundarbans investigation area

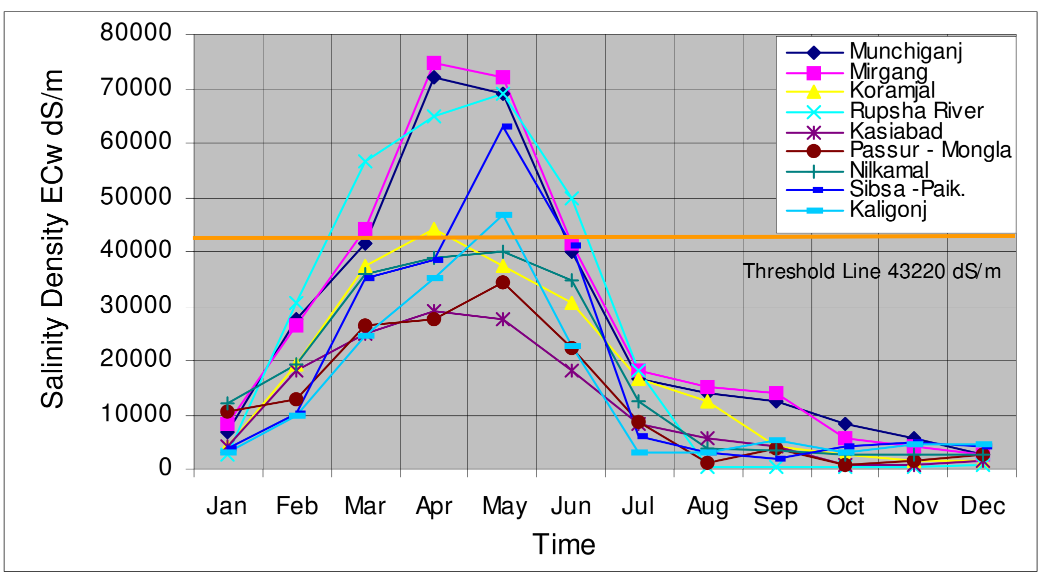


Figure 3.20 Water salinity at 9 sites in the of Sundarbans region in 2003

The survey samples were collected from 9 different sites (Figure 3.19) such as Munchiganj, Mirgang, Koramjal, Rupsha River, Kasiabad, Passur-Mongla, Nilkamal, Sibsa - Paikgacha and Kaliganj points. The survey results are shown in the graphs in Figure 3.20 and Figure 3.21.The results in the graphs have shown that until February the water salinity rate has been less than 27660.8 ECw dS/m and the highest density over 74684.16 ECw dS/m was found in Mirgang and Munchiganj which is situated in the west-north part of the Sundarbans forest. Water salinity increased rapidly and varied from east to west and north to south.

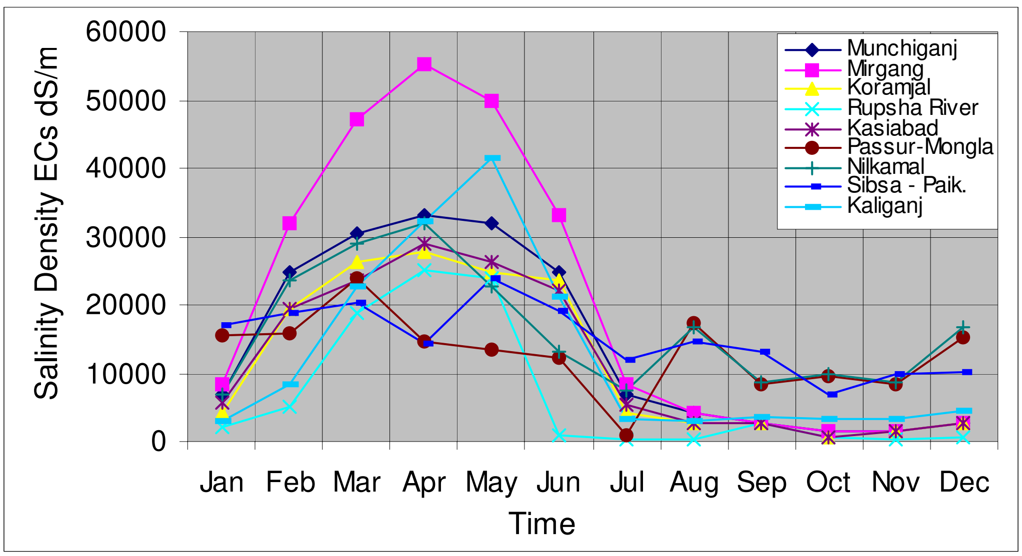


Figure 3.21 The soil salinity at 9 sites in the Sundarbans region in 2003

Whereas the threshold value of water salinity for most of the mangrove plants and animals is 43220 ECw dS/m. The soil samples were also collected from the same 9 water sample sites (Figure 3.19) The soil salinity increasing rates are also similar in trends which is depicted in (Figure 3. 21), the real scenarios in the Figure 3.20 where the highest rate of ECs is 55321.6 ECs dS/m was found at Mirgang and the second highest rate of soil salinity ECs is 41629.50 dS/m was found at Kaligonj point it is situated out side of the Sundarbans (Figure 3.19).

3.3.5 Scarcity of upstream freshwater and its impacts in the downstream

The shortage of water in the Ganges catchment area is one of the major environmental hazards which have been recognised recently. Considering the requirements of water, India needs 14,647 m^3/sec water for irrigation in addition to 1133 m^3/sec which is needed for the preservation of Calcutta port.

Bangladesh also needs water from the Ganges basin in the dry season to protect the down stream ecosystems in the region for example for the conservation of the world famous mangrove wetland ecosystems. The flow during the peak period rises to over two million m^3/sec which decreases to some 1700 m^3/sec to 1841 m^3/sec during the winter months at the point of entry to the delta (Begum, 1987). The water maintains the environment and the ecology of the region and constitutes the main potential for development.

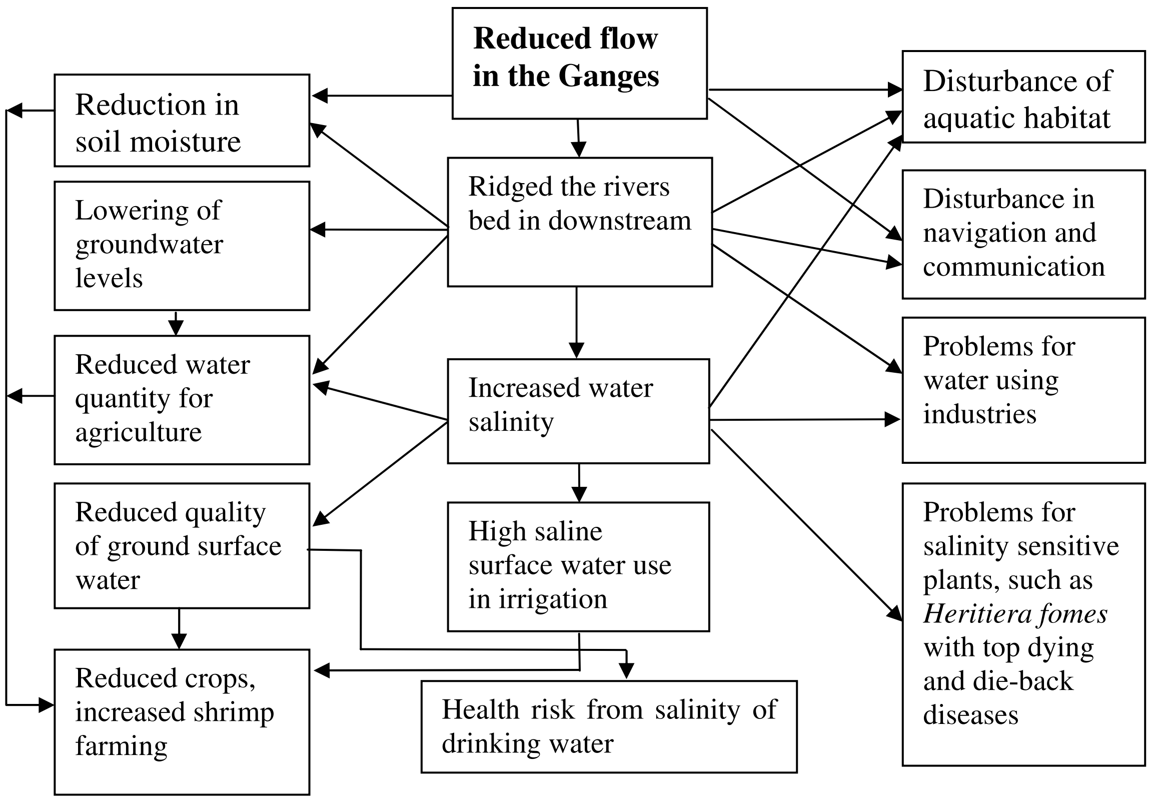


Figure 3.22 Reduced fresh water flow and impact on ecosystems (after Ben, 1995)

The impact of commissioning the Farakka Barrage on agricultural production is severe. There were the impacts on river morphology, groundwater, salinity, fishery, forestry, ecology, navigation, industry and health (Figure 3.22). The conceptual model shows the impacts of salinity intrusion due to the shortage of Gorai river's discharge in the dry seasion (February to May). An extreme variation of availability of water in the dry and in the wet seasons is being observed. Consequently, scarcity of water during the dry season and widespread flowing from excess water in the wet season damage the crops and ecosystems (Hoque and Alam, 1995).

3.4 Threats to the Sundarbans

The scarcity of the Ganges water flows in the Sundarbans region is a challenge for cultural landscapes, biodiversity and wetlands ecosystems of the coastal environment. The biota of the Sundarbans mangrove wetlands are highly influenced by salinity regime of surface and groundwater systems and more significantly of water and soil. The vegetation of the particular area can be dominated due to high salinity intrusion. Natural regeneration of vegetation and forest succession also depends on salinity regime (Karim, 1994). Continuous water and soil salinity increasing, the loss of biodiversity and degrading the quality of water and soil of the entire area is creating threats to ecosystems (Curry and Mcguire, 2002). The water quality and the analytical results of water pH in the Sundarbans region was found to be 6.0 to 7.0 which were considered under neutral acidic reaction class, and for the soil analytical result analysis the Soil pH which was 7.10 to 7.70 were considered under neutral and saline alkali. The organic matter was found 0.88 % to 1.34 % which was a very low concentration. The concentration of Nitrogen (N) was 0.07 % to 0.08 % which was very low comparing to other places in the coastal region and Zinc (Z) concentrations was 2.6 mg/g to 5.0 mg/g which was very high for mangrove plants production and growth. The other values of water quality parameters including NaCl, BOD, COD and NH_3-N have crossed the considerable limits of standard. As a whole the elements of ecosystems are being affected through salinity intrusion inside and outside of the Sundarbans. The Ganges fresh water supply and policy is consequently a strategic and political issue between Bangladesh and India. For this reason the stability of ecology and ecosystems balance could deepend on the Ganges fresh water supply in the downstream. Otherwise this could be in turn effects on the long-term sustainability of wetlands ecosystems management in the whole region.

3.4.1 Human influences and negative impacts in the Sundarbans

The inadequate water resources management in the Sundarbans has evolved under the influence of human activities and reduced salinity, which used to be maintained by huge amounts of fresh water flow into the downstream rivers. The basin is an area of strategic economic and development importance, marked by socio-economic disparities and environmental vulnerabilities. The optimisation and harmonisation of competing water uses, power generation, irrigation, fishing, tourism, waste dilution, household and industrial water supply and other, including environmental uses has been a constant challenge for the basin stakeholders. The continuous freshwater reducing process in the Ganges transboundary catchment has occurred for the last three decades (Joseph, 2006).

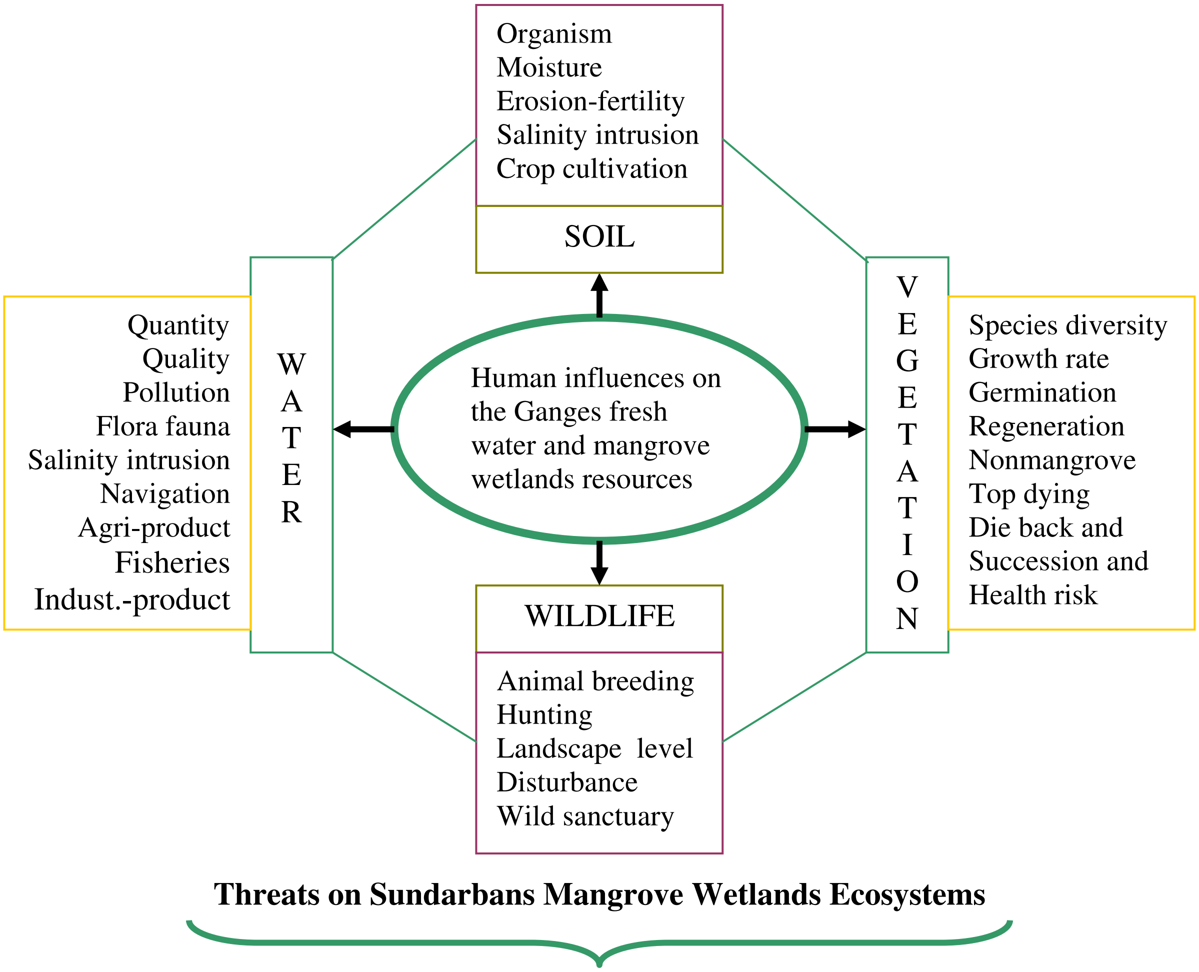


Figure 3.23 The ecological and socio impact structure of the Sundarbans mangrove forest (Souce: after Islam, 2003)

Mangrove ecosystems are under stress by reason of human activity both within and outside the ecosystems. The abnormal quantity of reduction of the Ganges water due to the Farakka Barrage and other dams that were constructed caused the reduction of fresh water flows to the Sundarbans. As a result increased salinity and alkalinity have damaged vegetation, agricultural cropping pattern and changed the landscapes in the Sundarbans region. The inadequate management of the Sundarbans natural resources has negative impacts on environmental, ecological, geological, geomorphologic, social and cultural issues. The impact of soils starts with the destruction of surface organic matter and of soil fertility for mangrove plants production.

The changes alter basic soil characteristics related to aerations, temperature, moisture and the organisms that live in the soil. The diagram (Figure 3.23) is showing the interaction between the four vital elements of ecosystems and the negative effects of ecosystems in the Sundarbans case. The figure displays 4 core elements of ecosystem such as soil, water, vegetation and wildlife which are natural resources in the Sundarbans and has a strong relation between fresh water and human influence. Down to shortage of fresh water in the Ganges upstream and the degradation of the water quality, the quality of these core elements of ecosystems is damaging.

3.4.2 The conceptual model of threatened Sundarbans ecosystems

An extreme variation of availability of water in the dry seasons is being observed. Consequently, scarcity of water during the dry season and widespread flowing from excess water in the wet season damage the crops and ecosystems (Hoque and Alam, 1995). The water maintains the environment and the ecology of the region and constitutes the main potential for development.

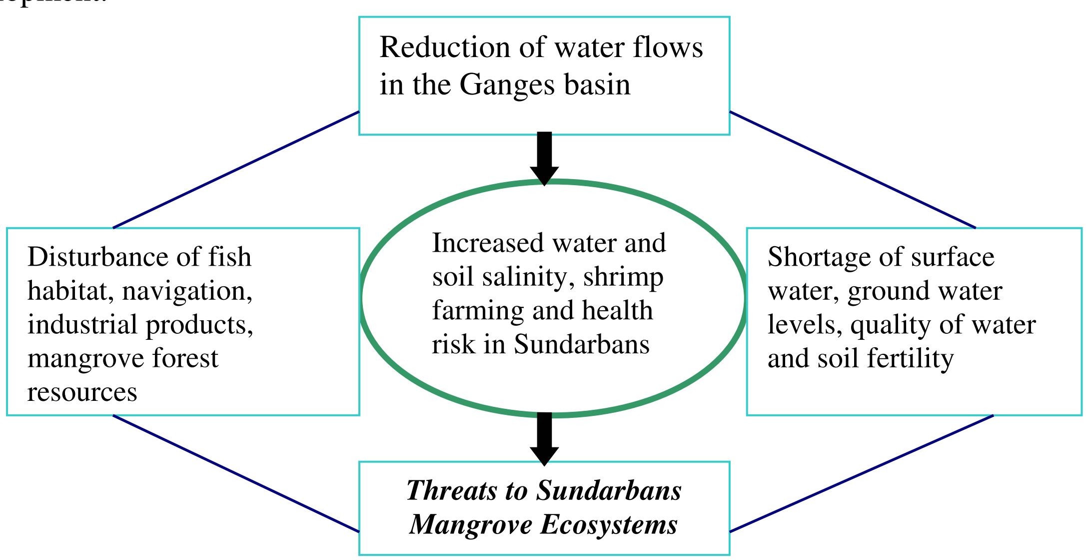


Figure 3.24 The conceptual model of threatened ecosystems in the Sundarbans

The elements of biotic and abiotic functions are affected by reduced fresh water flows in the downstream of the Ganges River in Bangladesh. The following conceptual model (Figure 3.24) is showing the environmental problems in the practical field. The reduction of Ganges water in the basin and the substantial use of natural resources are the main problems posing threats to the elements of the ecosystems. In reality the Ganges water is receding in an abnormal rate and it is the main reason for fresh water reduction from the upstream river basins. Massive negative impacts are affecting the mangrove ecosystems in the Sundarbans region. The main impacts have been clearly mentioned in the previous sub chapter.

3.4.3 Pressure, problems and substantial uses of natural resources

The Sundarbans mangrove forest has been exploited for the past few centuries. But bit attentions have been paid to the improvement of the mangrove forest and its wetlands resources. On the other hand the forest has been deteriorated in recent decades. The mangrove forest has been over-cut and exploited though it is meant to be managed on a sustained yield basis. The harvesting could not be properly regulated because of the demand of the people. Wildlife populations have declined greatly and no effective step has yet been taken for adequate management and conservation of wildlife. The fishery sector of the Sundarbans is playing a potential role for fish culture, but no attention has been paid to the improvement of this important natural resource. The surrounding environmental condition of the forest area is under continuous degree of change by reason of global warming, salinity intrusion and shortage of fresh water flows in the upstream and natural calamities in the coastal areas. These have posed serious threat to sustainable management of the Sundarbans (Siddiqi and Das, 2000; Siddiqi, 2001). The problems and pressures of the Sundarbans are diverse including, ecological, economical, management, regeneration, mortality of trees, sedimentation, tourism, water and soil salinity, water pollution and research activities etc.

- Wetland ecosystems have historically been considered as wastelands, unworthy of consideration for conservation. As a result, wetlands have frequently been altered or lost because their ecological functions and resulting values to society have not been understood (Siddiqi, 1994).
- Deforestation of mangroves as result of shrimp farming, salt farming and agriculture adversely affects marine fisheries production and leads to a loss of biodiversity and landscape changing and the livelihood of over 6 million people who depend on mangrove resources directly in the coastal region in Bangladesh (Anon, 1995).

- The Sundarbans Biodiversity Conservation Project (SBCP) does not give due consideration to the possible destructive effects of tourism on such a highly sensitive ecosystems as the mangrove forest.

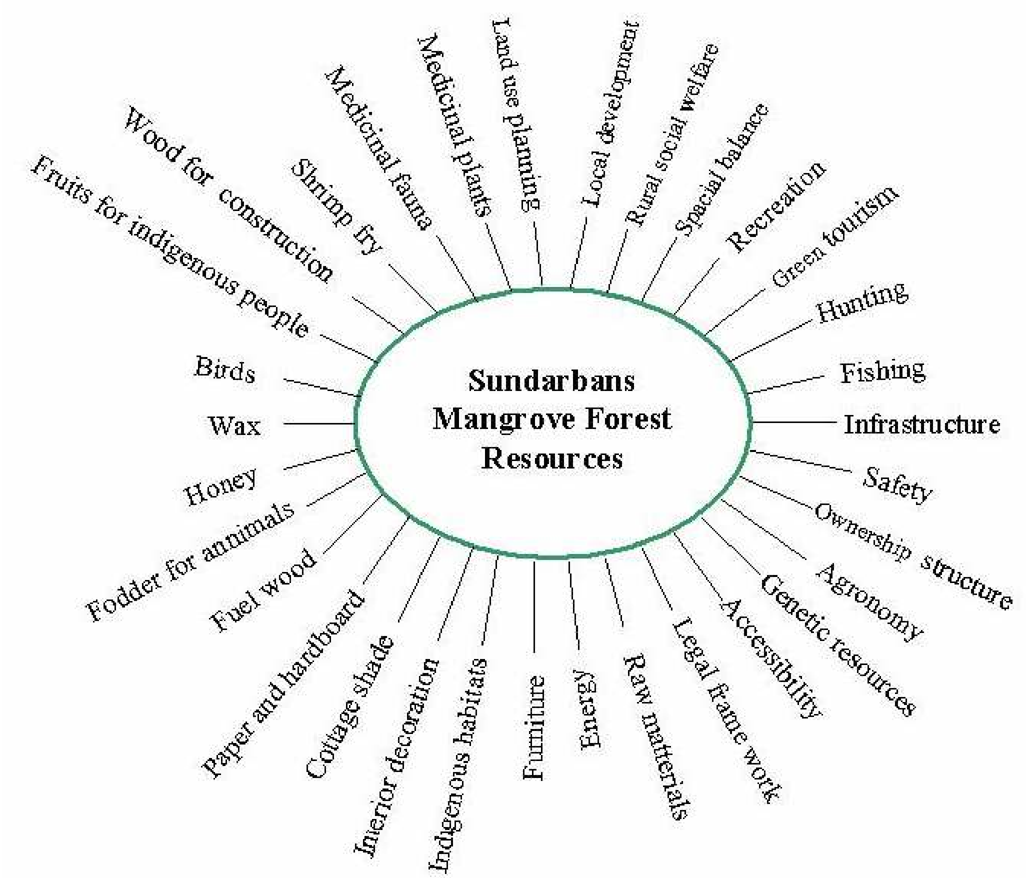


Figure 3.25 Substantial mangrove wetlands resource usage in the Sundarbans

- The method of collection of shrimp fry post larvae from the rivers in and around the Sundarbans is inefficient, generally women and children are engaged in this occupation catch with the fry in thin-mesh nets, which is harmful to other fry species when they are in the same thin nets and gradually they are destroying. It is a massive damage of aquatic biodiversity in creeks and around the Sundarbans and threatens the ecosystems.

The increase of salinity due to a lack of fresh water flows from upstream has caused damages to the Sundarbans and its coastal wetlands ecosystems.

3.5 Existing management strategies for the Sundarbans mangroves

The early management of the Sundarbans was confined to the realisation of revenue on the export of forest produce from the area. A large scale deforestation and destruction of wild life habitats and indiscriminate hunting caused a great decline in population size of animals and drew attention to the Government and the Sundarbans and was declared as a reserved forest in 1878 under the Forest Act VII of 1865 (Siddiqi and Das, 2000; Siddiqi, 2001). The decline in forest cannot recover itself with proper management further deterioration of the status of the mangrove wildlife habitats can be prevented. The first management plan of the Sundarbans came into force from 1893-98 (Heining's working plan). This working plan was revised from 1903-04 (Lloyd's working scheme) and again from 1906-07 (Farrington's Working Scheme). A regular working plan was prepared by Trafford for the period from 1912-13 to 1931-32 and his plan divided the whole forests into two working circles (Eastern and western) covering saline areas and relatively poor and less saline areas with good qualities trees. The plan of Curtis came into existence in 1931; a large volume of data was collected for this working plan (Curtis, 1933). The aim of this plan was managing the production of timber, fuel wood and thatching materials and the exploitation diameter was fixed for different site quality. A 20 years felling cycle for less saline areas and 30 years for moderate saline areas was prescribed. Choudhury's modification plan came into being when felling was maintained as forest management systems but it expired in 1947. A forest inventory of the Sundarbans was completed in 1960 based on aerial photographs (Choudhury, 1968; Siddiqi and Das, 2000).

The present working plan (1960 -1980) was prepared by Choudhury in 1968 from the data of that inventory. The working plan divides the forest into Gewa (*Excoecaria agallocha*) Sundri (*Heritiera fomes*) and Keora (*Sonneratia apetala*) working circles. The whole Sundarbans is divided into 4 ranges namely Saronkhola range area 1309.98 km^2, Chandpai range area 1000.21 km^2, Khulna-Nalianala range area 1613.45 km^2, and Shatkhira-Burigoalini range area 1849.92 km^2 (Hossain and Acharya, 1994. The modified management plan was redeveloped in 1980 and is still in use. The management plan divides the forest into Gewa (*Excoecaria agallocha*) Sundri (*Heritiera fomes*) and Keora (*Sonneratia apetala*) working circles. The felling cycle is 20 years and yield is regulated by area. The Sundarbans mangrove wetlands ecosystems are managed maintained and preserved by the forest department under the Ministry of Environment and Forests (MoEF) by application of the Forest Act 1927 and the Forest Amendment Act in 1960. Currently the Ministry of Environment and Forest with the co-operation of IUCN has drafted a national wetlands policy framework, which has not yet been implemented. The objectives and the main features of this policy include the following issues;

- Maintenance of biodiversity in the reserve forest
- Conservation and maintenance of soil, water resources and ecosystems health and vitality
- Maintenance of ecosystems functions, and ecological process in the coastal wetlands
- Promotion of economical development through stakeholders participation and
- Principles for sustainable natural resources utilisation and management.
- Maintenance of evolutionary process and accommodating human use in light of the previous issues.
- Development of the legal, instrumental and economic frame work for mangrove wetlands conservation and sustainable management.

Summing up, it appears that a number of physio-chemical factors are involved in mangrove growth and its ecosystems development. Considering the present environmental condition, an integrated resource management and development approach will be appropriate for improving the existing management situation. After a close observation it has been confirmed that the management systems in the Sundarbans mainly aims to manage the plant resources of the forest. The other important aspects of ecosystems such as wildlife, mangrove fauna, fishery, shrimp and fry collection, tourism, biodiversity protection, conservation of natural world heritage site location and socio-economic of the surrounding population have not yet been taken into account or due consideration.

Chapter 4
Modelling of Water Salinity

4.1 Water salinity modelling in the Sundarbans Rivers

In the Sundarbans mangrove wetland forest region there are creeks, channels and rivers making a total of 430 available in the region. Once all the canals and rivers were connected with each other and carrying fresh water from one place to another such as from the northern upstream to southern downstream and eastern to western side of the forest area (Siddiqi, 2001). There are 29 large rivers which forms the major portion of the Sundarbans rivers. They are located at different areas of the forest and they converge at the Bay of Bengal. There are 13 important rivers and their basins that play an influential role in balancing the Sundarbans ecosystems. For this reason these 13 rivers were chosen for water salinity modelling using time series of Fourier polynomial approximation method. The location of these selected rivers represents the major portion of the case study area. The rivers have influential role in balancing the mangrove ecosystems and on the coastal environment as well. The location of the rivers and their distribution network pattern covers the whole Sundarbans region. The detail methodology of water salinity modelling has been discussed in the following sub-chapters. The general conception and the meaning of model is the abstraction of reality. A model can be considered as a synthesis of elements of knowledge about a system. Models are able to provide new knowledge, about the reactions and properties of the entire systems, which is useful for the development of ecosystem theory. The quality of the model is therefore very dependent on the extent of knowledge about the elements of the systems and the available data (Jörgensen and Müller, 2000). A model is therefore nessecary for any kind of problem solving and an adequate management planning (Gnauck, 2000). Water salinity model is the analysis of salinity intrusion in water. This long time salinity intrusional behaviour in water is possible through salinity simulation and modelling and it can be measured with technical approaches. With such approach, the behaviour of salinity in water for a long time period is shown in a graph which is defined as a water salinity model. The time series model is one of the popular models for such interesting field of investigation. Time series curves which are of cyclic nature often arise when monitoring salinity intrusion of a process. Time series methods take into account the nature of the data collected. In time series models there are some fundamental approaches for analysing models. Generation of river water salinity data can be frequently observed in time series behaviour and an ordered sequence of values of variable at equally spaced time intervals are also generated. The use of time series models are two folds, firstly obtain an understanding of the underlying forces and structure that produced the observed data, and secondly fit a model and proceed to forcasting, monitoring or even feedback and feedforward control. Time series analysis is used for many applications in different environm-

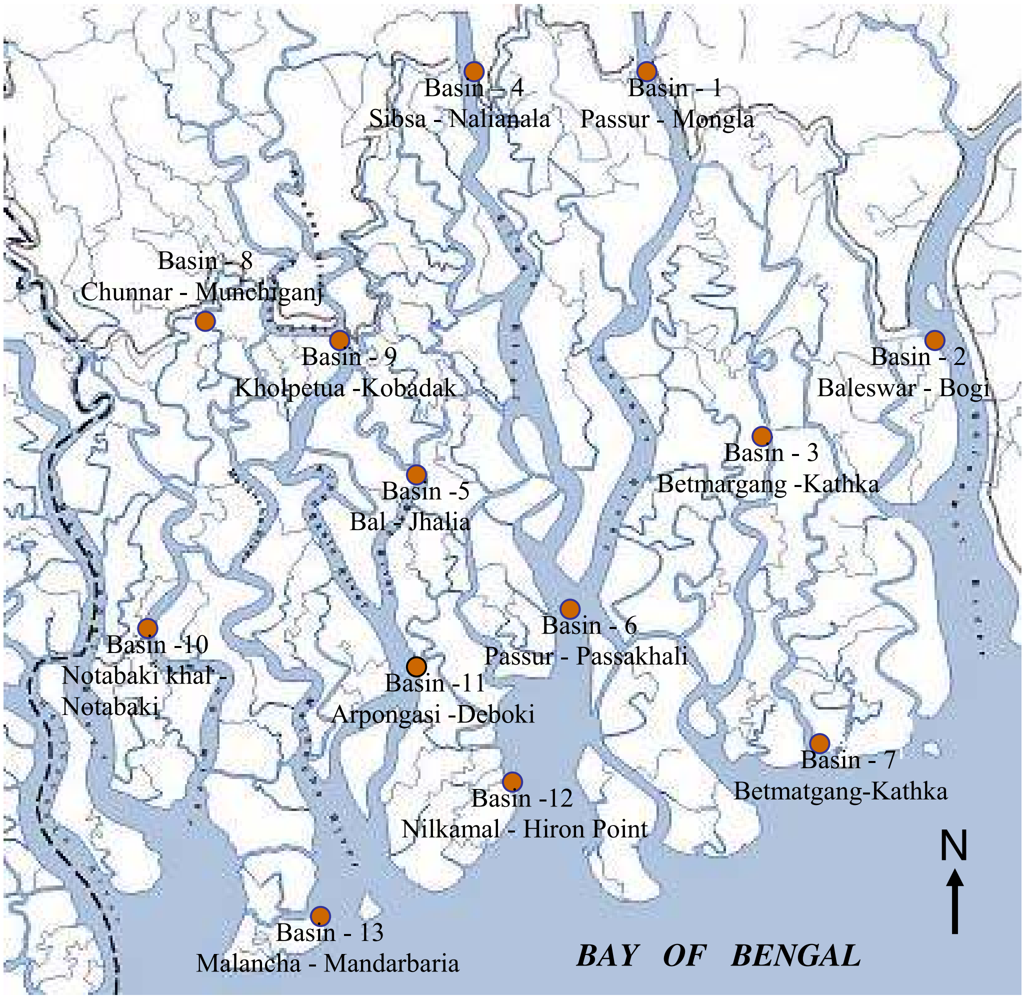


Figure 4.1 Location of water salinity samples collection in 13 river's basins

-ental and economical fields. There are many methods used to model and forcast time series. The Fourier polynomial time series model is one of the appropreate approaches for analysing the models. In the Sundarbans rivers water salinity modelling, the Fourier polynomial time series model has been considered for water salinity approximation analysis. This model has a cycling behaviour, which makes it easy to understand the cyclic process of water salinity. This technique has strong appreciation for periodic cycling behaviour of a particular interval of time. The Fourier model is one of the scientific approach, by which it is possible to forecast the future situation and possibly to make a long term management plan for natural resources stabilization such as maintain the ecosystems. The closed boundaries with consideration of rainfall runoff have been treated as closed in the salinity model. In the southern part of the model areas, all the tidal boundaries were considered as open and salinity concentrations were specified from the observed data. Out of 29 rivers in the case study area, the observed data were collected from 13 influential rivers which are shown in the investigated area. The surface water flow in the rivers of the Sundarbans area mainly comes from the Ganges-Padma at the off take of Gorai through the Passur River in the Sundarbans and Gorai-Madhumati and from the lower Meghna through the Swarupkati-Kocha River. Some other sources are from the local rivers surface flows of the local catchment areas. Some rivers that are in the catchment areas like Bhairab, Bhadra, Chitra, Khulpetua etc normally receive runoff water from their own catchment area. Salinity is the amount of dissolved salts present in water. It reflects the dominant forcing functions of freshwater discharge and oceanic exchange.

4.2 Fourier polynomial method

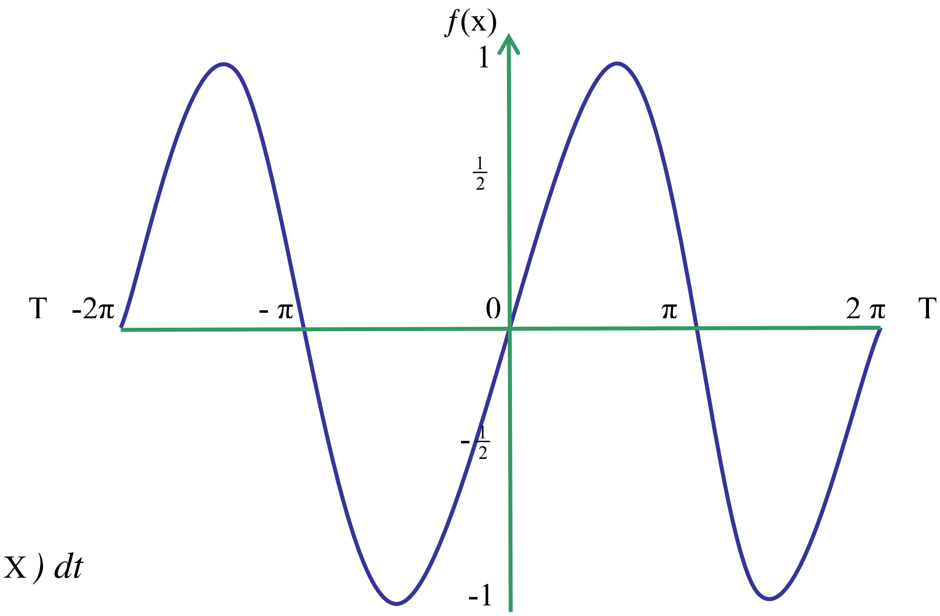
Considering the data which were recorded over some interval of time, it will be necessary to choose a model that is periodic. In analogy to the “polynomials of best fit” it is possible to write down a model that consists of a sum of sine and cosine finctions that best fit the given data. It is necessary to decide with time, how many sines and cosines needs to be used in the model approximation. At the same time it is also necessary to decide on the degree of the polynomial model which best fit the data. The model which consists of trigonometric functions is called Fourier Polynomials. These models are widely used in engineering, physics and applied sciences to approximate process that are periodic.

According to the theory development by Fourier, any periodic function F(X), with period T, may be represented by an infinite series of the form

$$F(X) = \frac{\partial o}{2} + \sum_{n=1}^{m} (\partial n \cos nw_T X + bn \sin nw_T X)$$

Where the coefficients ∂o, ∂n and bn for a given periodic function F(X) are calculated by the formulas.

$$\omega = \frac{2\pi}{T}$$



$$a_0 = \frac{2}{T}\int_o^T F(X)\,dt$$

$$an = \frac{2}{T}\int_o^T F(X)\cos nw_T x\,dt \qquad n = 1, 2, \ldots\ldots\ldots\ldots\ldots m$$

$$bn = \frac{2}{T}\int_o^T F(X)\sin nw_T x\,dt \qquad n = 1, 2, \ldots\ldots\ldots\ldots\ldots m$$

It should be noted that the first coefficient a_0 is twice the average of the function F(X) over one period. This series is called the Fourier series and the coefficients are called the Fourier coefficients.

The general Fourier polynomial approximation of order 1 to 8 models were considered to generate results for the water salinity model of the Sundarbans. In most cases the 8^{th} order approximation was found to produce the best results and it therefore dominated all other models. The Fourier polynomial approximation of 8^{th} order is given by the following equation;

$$\begin{aligned} f(x) = \; & a_0 + a_1*\cos(x*\omega) + b_1*\sin(x*\omega) + \\ & a_2*\cos(2*x*\omega) + b_2*\sin(2*x*\omega) + a_3*\cos(3*x*\omega) + b_3*\sin(3*x*\omega) + \\ & a_4*\cos(4*x*\omega) + b_4*\sin(4*x*\omega) + a_5*\cos(5*x*\omega) + b_5*\sin(5*x*\omega) + \\ & a_6*\cos(6*x*\omega) + b_6*\sin(6*x*\omega) + a_7*\cos(7*x*\omega) + b_7*\sin(7*x*\omega) + \\ & a_8*\cos(8*x*\omega) + b_8*\sin(8*x*\omega) \end{aligned}$$

In the research the Fourier polynomial approximation is carriedout based on data and different Fourier polynomial approximation orders.

4.3 Data used

In writing this dissertation, it was necessary to collect data and information from different sources. The general data and information about the case study area have been used in the introductory chapter and chapter three. The specific data, information about river water samples which were collected from the selected 13 rivers from Sundarbans are extensively discussed in chapter 4, which is the core chapter of this dissertation. The rivers water salinity data were collected from the Institute of Water Management (IWM, 2003) in Dhaka. In the Sundarbans area, there are 29 potential rivers that protect the coastal mangrove ecosystems and cultural landscapes. Considering the availability and the number of samples data and missing values, only 13 important rivers were selected for salinity modelling. The major rivers (29 rivers) in the Sundarbans extend their flows across the three ecological zones in the entire forest area. All the rivers are located within three ecological boundaries, the following map (Figure 3.17) and the ecological boundaries shows the accurate basin and flow direction. Water samples were collected from 3 important rivers out of 8 rivers in the less saline zone such as Passur-Mongla River, Baleswar-Bogi River, and Selagang-Harintana River; 4 potential Rivers out of 10 rivers in the moderate saline zone like Sibsa-Nalianala River, Bal-Jhalia River, Passur-Passakhali River, Betmargang-Kathka River; and 6 potential rivers out of 11 rivers from high saline zone such as Chunnar-Munchiganj River, Kholpetua-Kobadak River, Notabakikhal-Notabaki River, Nilkamal-Hironpoint River and Malancha-Mandarbaria Rivers. These 13 rivers which are 45% of the 29 important rivers in Sundarbans are playing an incomparable role in balancing the mangrove ecosystems. Every selected river has 4 years (in average) continuous similar intervals data and information which is comfortable and acceptable to work with time series modelling through Fourier polynomial approximation. Fourier polynomial model has a cyclic behaviour which is appropriate for realizing and understanding the real situations. Through this Fourier polynomial model it can be possible to forecast the future trends of increasing and decreasing rate of salinity. After selection of the 13 potential rivers, data and information on every rivers were processed and analysed with computer based excel programme, finally the missing values of all the rivers were identified through interpolation in excel. The missing values were replaced by approximation procedures, using interpolation methods. Table 4.1 shows the data rearrangement structure and other information of 13 river basins (Figure 4.1). All these rearranged and reconstructed data were used for developing the Fourier Polynomial time series model on every river (13 rivers) of the Sundarbans region. As an example the specific data collection methods of the Passur-Mongla River are given bellow.

Data of Passur-Mongla River

The Passur-Mongla River water data collection is important for assessing the quality of water interms of pollutant particles. The river water data from the selected source were collected at various intervals of time. The data were collected during inundation period, a condition which is known as flood slack. The data were collected from 2nd January 2002 to 30th August 2003. During the period of data collection, the 4 seasons of the year were considered, the raining season or wet season is the lowest salinity season and the dry season is the most important time for salinity intrusion. The data collection methods were on monthly basis. In every month, 20 samples were collected. The data collection frequency is every 1.5 days or every 36 hours. Data collection process was continuously carriedout during the 20 months duration. Data were collected in the early morning, noon and evening time. For example data collection process in the month of January 2002 are as follows: 1st day-salinity 7779.6 dS/m, 2nd day-salinity 7779.6 dS/m, 3rd day-salinity 7995.7 dS/m, 4th day-salinity 7995.7 dS/m, 5th day-salinity 8211.8 dS/m, 6th day-salinity 8211.8 dS/m, 7th day-salinity 4105.9 dS/m, 8th day-salinity 8644 dS/m, 9th day-salinity 8860.1 dS/m, 10th day salinity 10805 dS/m, 11th day-salinity 10588.9 dS/m, 12th day-salinity 9940.6 dS/m, 13th day-salinity 9940.6 dS/m, 14th day-salinity 10156.7 dS/m, 15th day-salinity 10372.8 dS/m, 16th day-salinity 10588.9 dS/m, 17th day-salinity 11453.3 dS/m, 18th day-salinity 12317.7 dS/m, 19th day-salinity 11453.3 dS/m, 20th day-salinity 12533.8 dS/m. The missing values in the Excel structure were replaced through approximation procedures, by interpolation methods. Having discussed the detail procedure about data collection methodology for Passur-Mongla River, the same method of data collection is adopted for the rest of the 12 rivers, namely, Baleswar-Bogi River, Selagang-Harintana River, Sibsa-Nalianala River, Bal-Jhalia River, Passur-Passakhali River, Betmargang-Kathka River, Chunnar-Munchiganj River, Kholpetua-Kobadak River, Notabaki khal-Notabaki River, Arpongasia-Deboki River, Nilkamal-Hironpoint River and Malancha-Mandarbaria River. A summary of the detail information about data collection procedure of 13 rivers can be found in Table 4.1. Figure 4.2, 4.3 and 4.4 shows the variation of the water salinities of the data collected from the 13 rivers found in the Sundarbans rivers.

Table 4.1 Data arrangement in a structural frame

River Basins	**Sample size**	**Period of time (duration of length)**	**Sampling interval**	**Missing values**	**Trophic state**
Basin – 1 Passur-Mongla	400	2nd Janu. 2002 to 30th Aug. 2003 (20 months)	1.5 days (36 hours)	No missing data	**Oligohaline/ Less saline** (NaCl 0-10805 dS/m)
Basin – 2 Baleswar-Bogi	350	2nd Feb. 2000 to 17th Aug. 2003 (43 months)	4 days	No missing data	
Basin – 3 Selagang-Harintana	500	2nd Janu. 2000 to 30th Aug. 2003 (44 months)	3 days	Reconstructed by interpolation	
Basin – 4 Sibsa-Nalianal	450	2nd Janu. 2000 to 30th Aug. 2003 (44 months)	3 days	No missing data	**Mesohaline / Moderately saline** (NaCl 10805-38898 dS/m)
Basin – 5 Bal-Jhalia	270	4th Sept. 2000 to 28th Oct. 2003 (38 months)	4 days	Reconstructed by interpolation	
Basin – **6** Passur-Passakhali	180	2nd Octo. 2001 to 30th July 2003 (22 months)	4 days	Reconstructed by interpolation	
Basin – **7** Betmargang-Kathka	12,771	1st Octo. 2000 to 31st July 2003 (34 months)	2 hours	Reconstructed by interpolation	
Basin – 8 Chunnar-Munchigonj	440	1st Janu 2000 to 30th Aug. 2003 (44 months)	3 days	Reconstructed by interpolation	**Polyhaline / Highly saline** (NaCl > 38898 dS/m)
Basin – 9 Kholpetua-Kabadak	430	8th Aug. 2000 to 30th Sept. 2003 (38 months)	3 days	No missing data	
Basin – 10 Notabakikhal-Notabaki	350	2nd Dec.2000 to 30thSept. 2003 (34 months)	3 days	Reconstructed by interpolation	
Basin – 11 Arpongasia -Deboki	180	8th Nov. 2001 to 31st Aug. 2003 (22 months)	4 days	Reconstructed by interpolation	
Basin – 12 Nilkamal - Hironpoin	12,706	1st Nov. 2000 to 31st Aug. 2003 (34 months)	2 hours	Reconstructed by interpolation	
Basin – 13 Malancha-Mandarbaria	12,960	1st Octo.2000 to 30th Sept. 2003 (36 months)	2 hours	Reconstructed by interpolation	

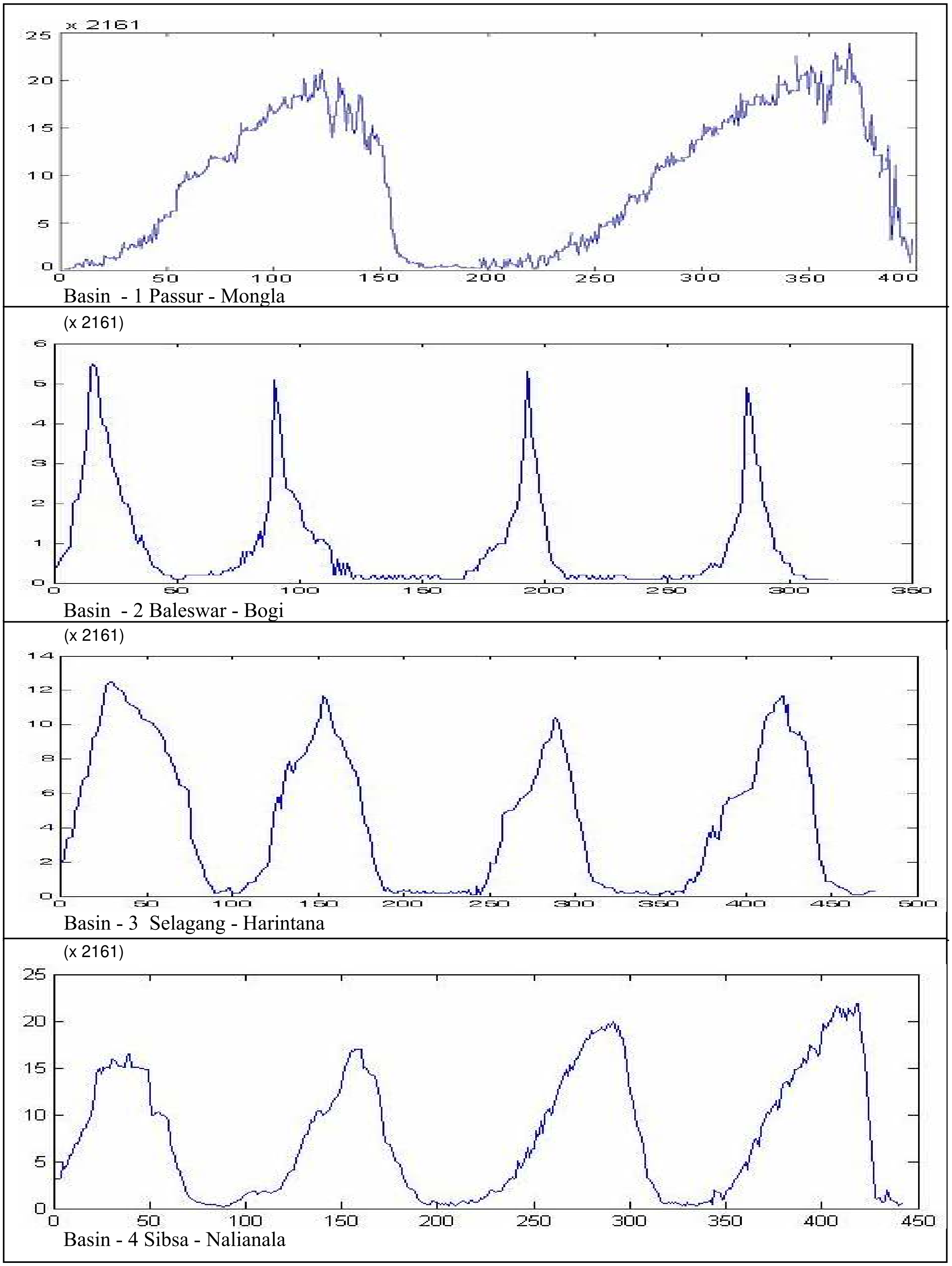


Figure 4.2 Water salinity of 4 rivers (basin 1- 4) in the Sundarbans

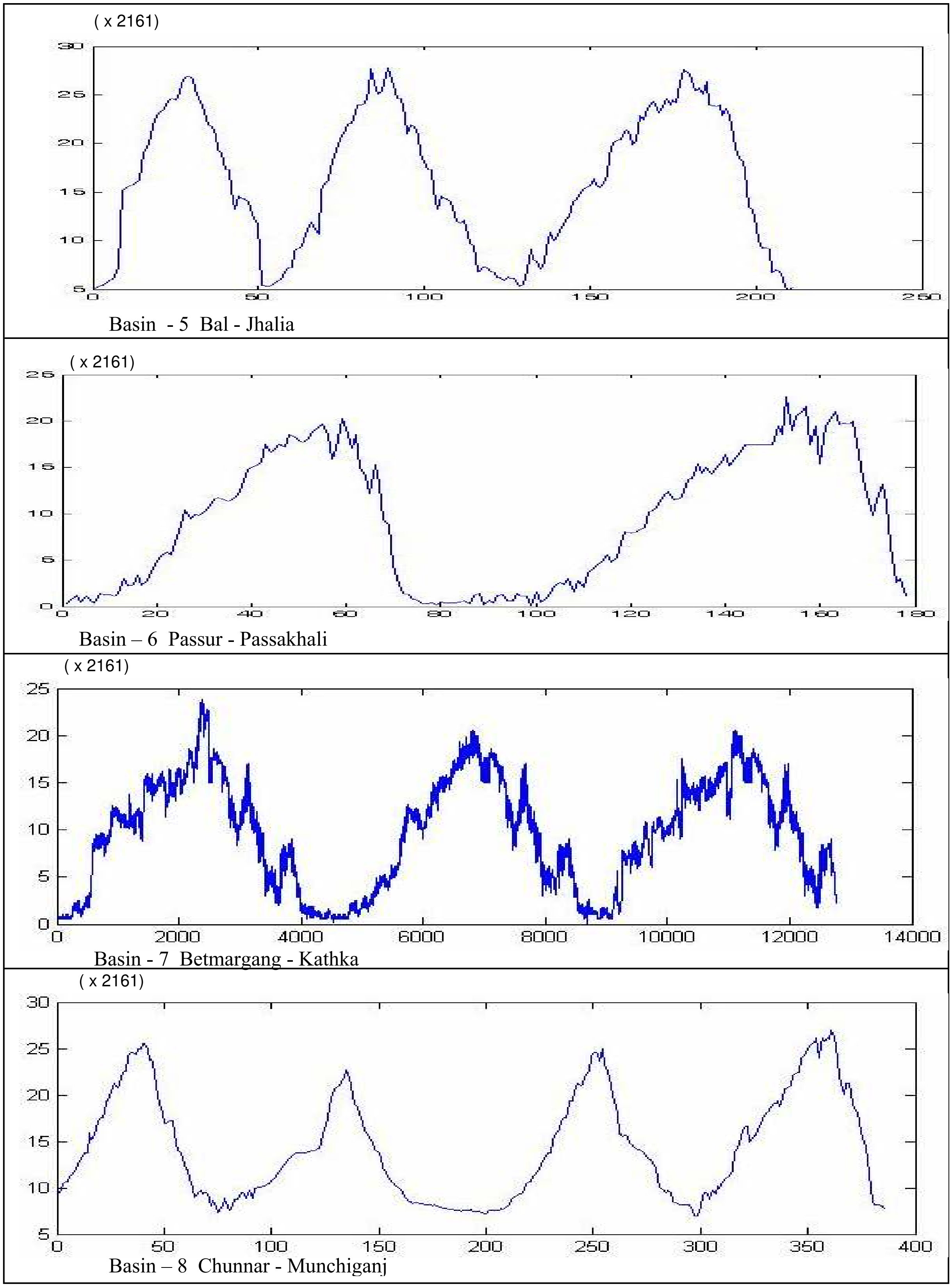


Figure 4.3 Water salinity of 4 rivers (Basin 5 - 8) in the Sundarbans

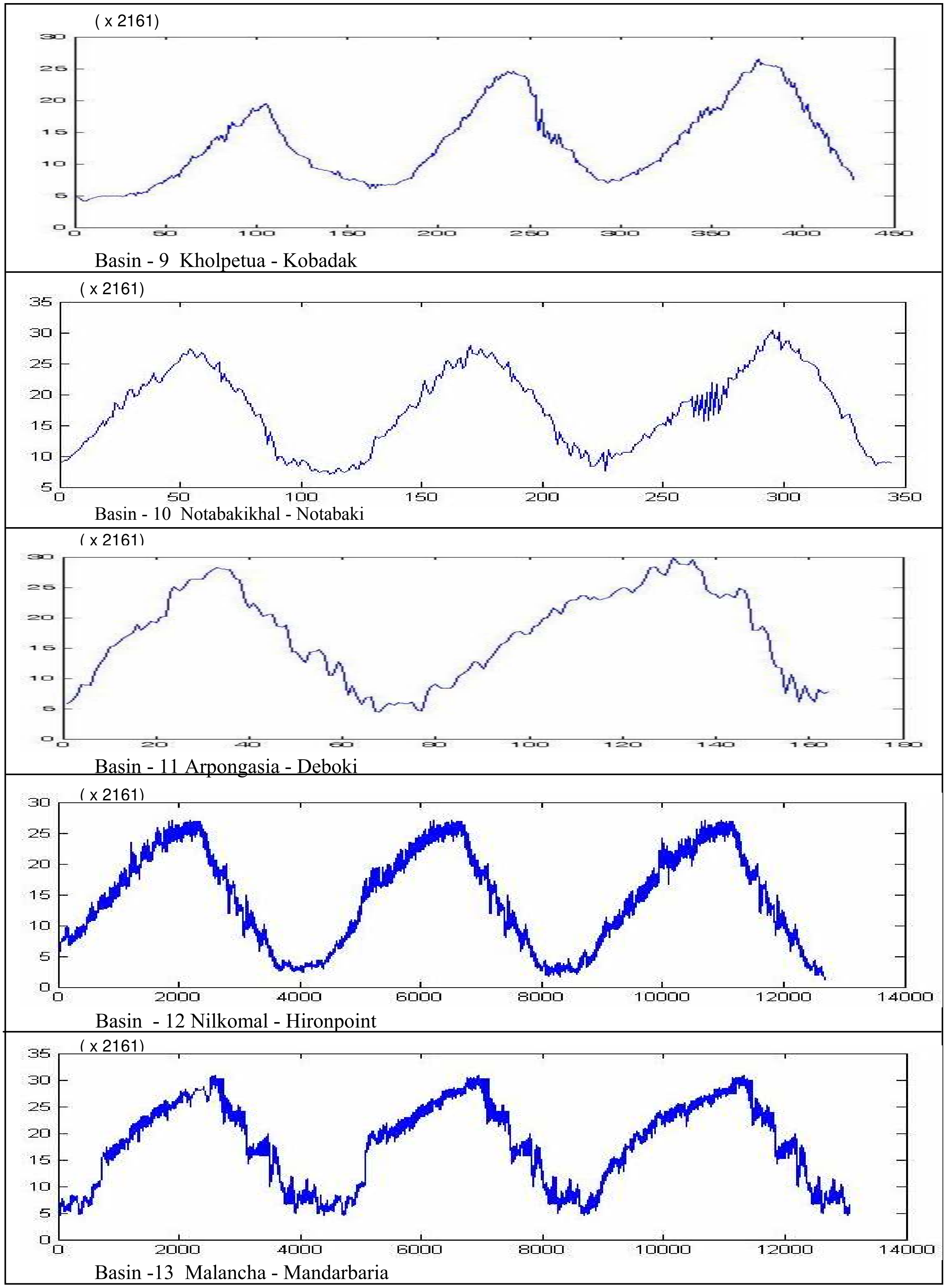


Figure 4.4 Water salinity of 5 rivers (Basin 9 -13) in the Sundarbans

MATLAB version 7.1 software which is a sophisticate mathematical model development software tool was used to develop Fourier polynomial water salinity models for the following rivers Passur-Mongla River, Baleswar-Bogi River, Selagang-Harintana River, Sibsa-Nalianala River, Bal-Jhalia River, Passur-Passakhali River, Betmargang-Kathka River, Chunar-Munchiganj River, Kholpetua-Kobadak River, Notabakikhal-Notabaki River, Arpongasia-Deboki River, Nilkamal-Hironpoint River and Malancha-Mandarbaria River. Table (Table 4.2) shows the basic results of Fourier polynomial approximation of time series water salinity models of 13 rivers on the Sundarbans. The specefic river based water salinity model results have been discussed more elborately in the following sub-chapters.

Table 4.2 Results of Fourier approximation of water salinity in the Sundarbans rivers

River Basins	Fourier model type	R^2	Adjusted R^2	RMSE	SSE	ω
Basin - 1 Passur - Mongla	Model 8	0.9399	0.9369	1.811	1109	0.02723
Basin - 2 Baleswar-Bogi	Model 8	0.8482	0.839	0.3357	31.44	0.02377
Basin - 3 Selagang - Harintana	Model 8	0.9408	0.9386	1.002	458.8	0.01679
Basin - 4 Sibsa - Nalianala	Model 8	0.9137	0.9098	2.014	1529	0.02861
Basin - 5 Bal - Jhalia	Model 8	0.6325	0.6002	4.508	3923	0.08369
Basin - 6 Passur - Passakhali	Model 6	0.9452	0.9352	1.735	1152	0.02719
Basin - 7 Betmargang - Kathka	Model 2	0.8641	0.864	2.118	5.727	0.001423
Basin - 8 Chunnar - Munchiganj	Model 8	0.955	0.9528	1.231	522.6	0.01985
Basin - 9 Kholpetua - Kabadak	Model 8	0.839	0.8323	2.511	2585	0.02258
Basin - 10 Notabakikhal - Notabaki	Model 2	0.9489	0.9481	1.478	738	0.05211
Basin - 11 Arpongasia - Deboki	Model 4	0.8884	0.8713	2.635	1119	0.0654
Basin - 12 Nilkamal-Hironpoint	Model 8	0.9802	0.9802	1.086	1.494	1.13
Basin - 13 Malancha - Mandarbaria	Model 2	0.9424	0.9423	1.881	4.624	0.001464

4.4 Result of water salinity modelling of the Sundarbans rivers

The ecological state of mangrove wetland ecosystem is the result of the complex interaction between physical, chemical and biological components or processes. To investigate the water salinity (NaCl) approximation in the Sundarbans rivers the Fourier polynomial approach has been used to recognised and monitors the salinity increasing trends. The collected data of 13 potential rivers of the Sundarbans was analysed usinging the Fourier polynomial approach. The time series data of the 13 rivers show the different type of salinity trends. As a whole, al most all the rivers of the Sundarbans region are carrying the increases rate of water and soil salinity in the case study area. Water salinity (NaCl) modelling was done using Fourier polynomial method (where MATLAB software) as a sopesticative tool for the development of water salinity modelling. The selected 13 rivers choosed for water salinity modelling on Passur-Mongla River, Baleswar-Bogi River, Selagang-Harintana River, Sibsa-Nalianala River, Bal-Jhalia River, Passur-Passakhali River, Betmargang-Kathka River, Chunnar-Munchiganj River, Kholpetua-Kobadak River, Notabakikhal-Notabaki River, Arpongasia-Deboki River, Nilkamal-Hironpoint River and Malancha-Mandarbaria River.

The result of water salinity approximation of 13 rivers showed increaging trends of salinity in the whole Sundarbans mangrove wetlands. This is the major issue for ecosystems protection in the Sundarbans. As a whole, water and soil salinity trends in the Sundarbans show the rapid increasing behaviour. The eastern part of the Sundarbans getting moderate saline, and the middle part is losing its moderate saline behaviour and becoming high saline zone.The increase in salinity in the northern area could be attributed to capillary upwards movement of solable salt, which is strong threats for agricultural cropping system and drinking water for the local community. The results of the water salinity models of 13 rivers in the Sundarbans were analysed separately and more elaborately in the following sub-chapters.

4.4.1 Water salinity modelling of Passur - Mongla River

The Passur-Mongla River is one of the biggest and important rivers in the Sundarbans region.

It is the largest fresh water supplier into the Sundarbans. The Gorai River is one of the tributary of the Ganges is connected with Passur River. The largers rivers like Passur and Sibsa have sandy beds and mud banks along the shore whereas the tidal creeks tend to be choked with very fine sediment. In the tidal rivers, suspended sediments are mainly composed of silt and clay. In the Sibsa River, the sizes of suspended sediments are finer than that of the Passur River. The sediments at Kabadak and Bhairab are very fine and sediment concentration is also very low, less than 21610 dS/m, even in the monsoon, while the sediment concentration along the Nabganga, Rupsha and Passur Rivers, range from 32415 dS/m to 43220 dS/m during the monsoon. During the dry season the suspended sediment does not vary significantly and concentration at Bardia is less than at Khulna and Mongla. In the dry season sediment concentration in the Passur River varies from 1080.5 dS/m to 21610 dS/m. The grain sizes in the Passur systems are coarser than in the Kabadak-Malancha sub systems. Therefore it is clear that the Passur River is carries huge volume of fresh water from upstream to the Sundarbans. When water velocity is much higher under this condition it can carry out coarser gain sizes of sediments.

The collected data of Passur-Mongla River was analysed using the Fourier polynomial method. The Fourier Polynomial has given the following 1 to 8 orders of models and out of these 8^{th} orders one can be considered as the best approximation of water salinity.

Models	**R-square**	**Error**
Model 1	0.8361	2.931
Model 2	0.894	2.363
Model 3	0.9248	1.996
Model 4	0.9301	1.931
Model 5	0.9354	1.861
Model 6	0.9375	1.836
Model 7	0.9383	1.829
Model 8	0.9399	1.811

All the Fourier models were developed and checked one after another. The Fourier model 8 is showing the best approximation considering the goodness of fits, the highest r-square value is 0.9399 and lowest error value is 1.811. In the model the graph shows the best condition of goodness of fit in Fourier order 8. The Fourier polynomial approximation 8^{th} order is given by the following equation;

$$f(x) = a_0 + a_1*\cos(x*\omega) + b_1*\sin(x*\omega) + a_2*\cos(2*x*\omega) + b_2*\sin(2*x*\omega) + a_3*\cos(3*x*\omega) + b_3*\sin(3*x*\omega) + a_4*\cos(4*x*\omega) + b_4*\sin(4*x*\omega) + a_5*\cos(5*x*\omega) + b_5*\sin(5*x*\omega) + a_6*\cos(6*x*\omega) + b_6*\sin(6*x*\omega) + a_7*\cos(7*x*\omega) + b_7*\sin(7*x*\omega) + a_8*\cos(8*x*\omega) + b_8*\sin(8*x*\omega)$$

Coefficients (with 95 % confidence bounds):

Coefficients	Value	95 % Confidence Value		Coefficients	Value	95 % Confidence Value	
		Lower	Upper			Lower	Upper
a_0	8.171	7.965	8.377	b_1	3.051	2.623	3.478
a_1	-9.058	2.623	-8.754	b_2	0.5036	0.1421	0.865
a_2	2.519	2.227	2.811	b_3	-1.696	-1.973	-1.419
a_3	-0.1494	-0.5027	0.204	b_4	0.4909	0.1849	0.797
a_4	-0.5579	-0.8558	-0.26	b_5	0.4075	0.09572	0.7193
a_5	0.5586	0.2621	0.8551	b_6	-0.4226	-0.698	0.0221
a_6	-0.01796	-0.3328	0.2969	b_7	0.1422	-0.1556	0.4401
a_7	-0.258	-0.5381	0.0221	b_8	0.1071	-0.1902	0.4045
a_8	0.4081	0.1296	0.6866	ω	0.02723	0.02707	0.02739

$$f(t) = 8.171 - 9.058 \cos(0.02723 t) + 3.051 \sin(0.02723 t) + 2.519 \cos(0.05446 t) + 0.5036 \sin(0.05446 t) - 0.1494 \cos(0.08169 t) - 1.696 \sin(0.08169 t) - 0.5579 \cos(0.10892 t) + 0.4909 \sin(0.10892 t) + 0.5586 \cos(0.13615 t) + 0.4075 \sin(0.13615 t) - 0.01796 \cos(0.16338 t) - 0.4226 \sin(0.16338 t) - 0.258 \cos(0.19061 t) + 0.1422 \sin(0.19061 t) + 0.4081 \cos(0.21784 t) + 0.1071 \sin(0.21784 t)$$

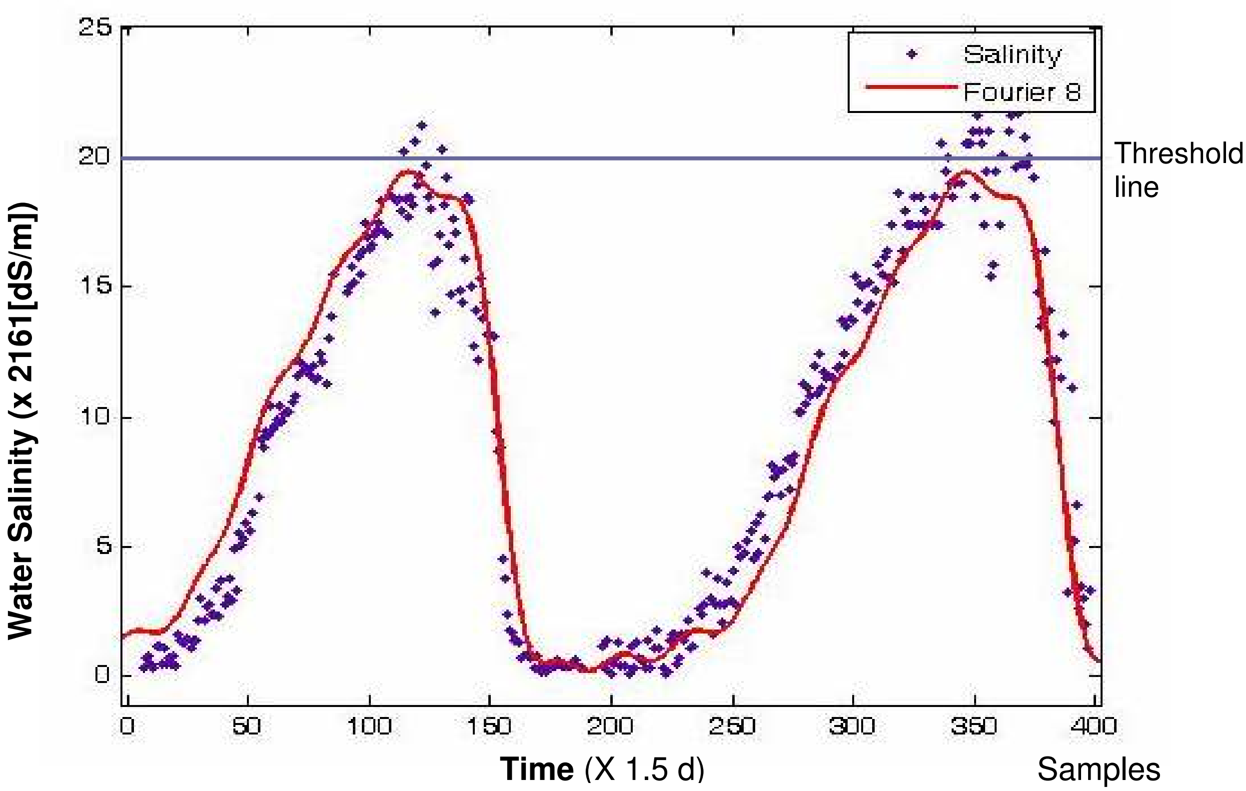


Figure 4.5 Fourier approximation of water salinity of Passur-Mongla River

The Fourier approximation shown in Figure 4.5 and has produced an acceptable result. Several external and internal environmental driving forces are responsible for this behaviour. The best approximation was found by a Fourier polynomial of eight order, where r^2 = 0.9399 and adjusted r^2 = 0.9369, Sum Square Error (SSE) = 1109 and Root Mean Square Error (RMSE) = 1.811 and ω = 0.02723.

In time series data analysis, the Fourier polynomial model 8 shows the best approximation where the polynomial graph indicate the highest salinity value in April is 45381 dS/m in 2002 and 51864 dS/m in April 2003. The difference of silinity increase between two years is 6483 dS/m. The highest salinity values normaly are identified in the dry season from February to June when a small volume of upstream fresh water flows in the downstream areas. In the graph the highest salinity values are in the marginal level of threshold value of 43220 dS/m.

The same methodology applied for Passur-Mongla River in developing the Fourier polynomial models 1- 8 with MATLAB software was also applied for the other 12 rivers namely Baleswar Bogi River, Selagang-Harintana River, Sibsa-Nalianala River, Bal-Jhalia River, Passur-Passakhali River, Betmargang-Khatka River, Chunnar-Munchiganj River, Kholpetua-Kabadak River, Notbakikhal-Notabaki River, Arpongasia-Deboki River, Nilkamal-Hironpoint River and Malancha-Mandarbaria River.

4.4.2 Water salinity modelling of Baleswar - Bogi River

The surface water flow of the rivers of the Sundarbans mainly comes from the Ganges-Padma through Gorai which splits from the Ganges 16 km downstream of the Hardinge Bridge. Gorai then passes through Kustia and Faridpur districts and divides at Bardia in the Jessor district. Some portion, almost 16 % of the flow of Gorai River meets the Haringhata-Baleswar estuary system at Madhumati River and the other 85 % of the flow through to join the Passur estuary at Nabaganga River. The Baleswar River is one of the biggest river in the Sundarbans region. It flows in the eastern boarder of the Sundarbans mangrove forest. It is the boarder between Sundarbans deltaic landscapes and the local settlements and agricultural fields. Baleswar River has an influential role informing the eastern river subsystems in the Sundarbans region. The area east of the Passur River and west of the Baleswar River represents this subsystem. The Baleswar River receives water from the Gages-Madhumati and from the lower Meghna.

The rearranged data of the Baleswar-Bogi River was used to develop the Fourier polynomial model. The Fourier Model-8 (Figure 4.6) is the most suitable and appropriate model for this river. In the model the highest R-square value is 0.8482 and the lowest value of Root Mean

Square Error is RMSE = 0.3357, Sum Square Error-SSE = 31.44, and ω = 0.02377. The Fourier polynomial approximation of 8th order is given by the following equation;

$$f(t) = 0.7354 + 0.04717 \cos(0.02377 t) + 0.2023 \sin(0.2377 t) - 0.1584 \cos(0.4754 t) + 0.05841 \sin(0.4754 t) + 0.46 \cos(0.7131 t) + 0.7545 \sin(0.7131 t) - 0.157 \cos(0.9508 t) + 0.2484 \sin(0.9508 t) - 0.2806 \cos(1.1885 t) - 0.1866 \sin(1.1885 t) - 0.2197 \cos(1.4262 t) + 0.2344 \sin(1.4262 t) - 0.164 \cos(1.6639 t) + 0.05642 \sin(1.6639 t) + 0.008994 \cos(1.9016 t) - 0.2473 \sin(1.9016 t)$$

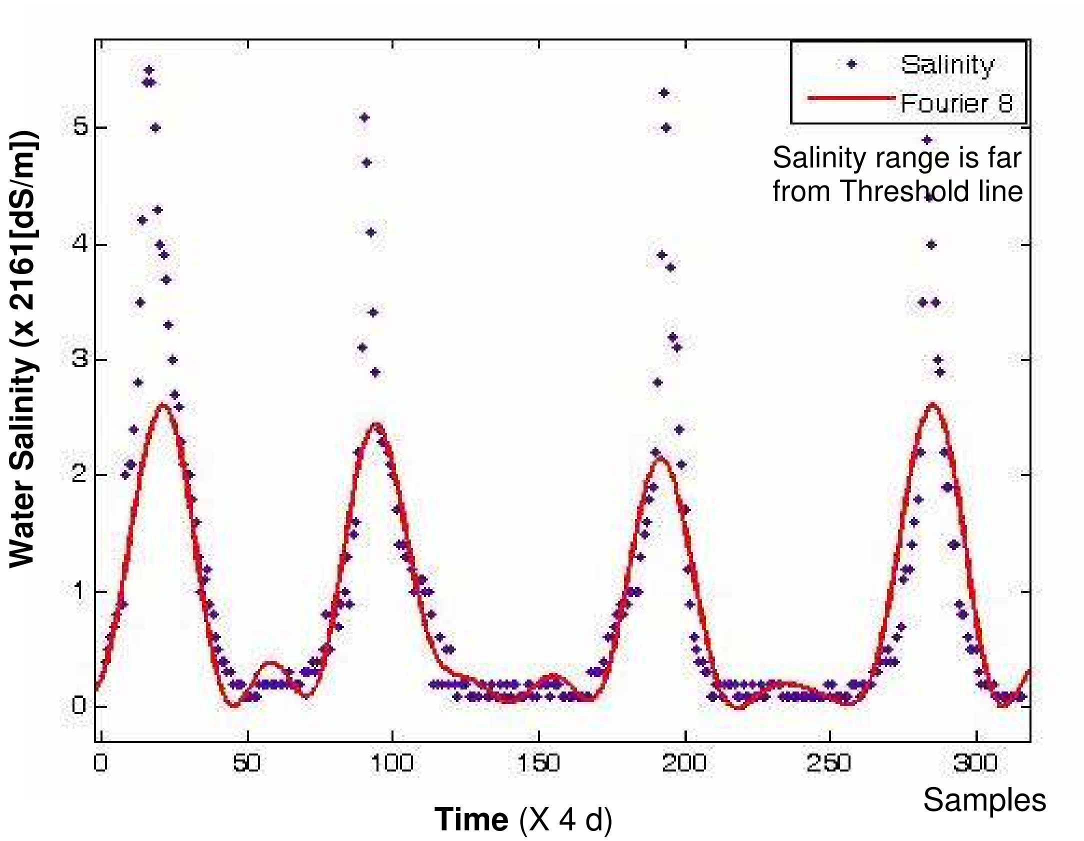


Figure 4. 6 Fourier approximation of water salinity of Baleswar-Bogi River

The Goodness of fit of Fourier polynomial model 8 (Figure 4.6) is, where r^2 = 0. 8482 and adjusted r^2 = 0.839, Sum Square Error-SSE = 31.44 and root mean square error-RMSE = 0.3357. Water salinity modelling for the river Baleswar-Bogi with Fourier polynomial model-8 was obsered to be the appropriate modeln for this river. In this model the graph is shows the dry season (February-June) with the highest salinity value of 11885.5 dS/m in 2000, 10805 dS/m in 2001, 10805 dS/m in 2002 and 10372.8 dS/m in 2003. The 4 years salinity model show the decreasing a rate from 2000 to 2003.

4.4.3 Water salinity modelling of Selagang - Harintana River

Selagang-Harintana River is a medium size river which is located it the eastern side of the less saline zone of the Sundarbans. The Selagang-Baleswar Rivers have reputation for fresh water supply in the south eastern zone. Selagang is very popular name and it is divided into three parts, one of which is Selagang Mrigamari which is tributary of Passur River. It comes from Passur starts to flows in the southern direction and meets with 4 rivers at Tambalbunia and again flows in the south direction towards the Selagang-Harintana, later it flows in the south western direction and in the downstream towards Selagang-Tiar Char. The river Sela gang carry some fundamental and basic result of water salinity in the Sundarbans rivers, which also play a vital role in the function of ecosystems in the coastal Sundarbans.

After data reconstruction of the Selagang-Harintana River, it was used to develop the Fourier polynomial model. The Fourier model 8 (Figure 4.7) has made the best approximation. In the model the highest r^2 value is 0.9408, adjusted r^2 = 0.9386, the lowest value of Root Mean Square Error-RMSE has found 1.002 and Sum Square Error- SSE = 458.8 and ω = 0.01679. The Fourier polynomial approximation 8^{th} order is given by the following equation; considering coefficient (with 95 % confidence bounds).

$$f(t) = 3.993 + 0.3744\cos(0.01679\,t) + 1.404\sin(0.01679\,t) - 0.3096\cos(0.03358\,t) + 0.3673\sin(0.03358\,t) - 0.5466\cos(0.05037\,t) + 4.835\sin(0.05037\,t) - 0.9341\cos(0.06716\,t) - 0.2288\sin(0.06716\,t) + 0.3884\cos(0.08395\,t) - 0.8346\sin(0.08395\,t) - 1\cos(0.10074\,t) - 0.3204\sin(0.10074\,t) + 0.1007\cos(0.11753\,t) + 0.2063\sin(0.11753\,t) + 0.0179\cos(0.13432\,t) + 0.4007\sin(0.13432\,t)$$

Water salinity modelling for the Selangang-Harintana River with the Fourier polynomial model-8 was found to be the appropriate model considering the best approximation. In this model the graph is shows the dry season (February-June) highest salinity value of 26364.2 dS/m in 2000, 25932 dS/m in 2001, 13871 dS/m in 2002 and 15132 dS/m in 2003. The water salinity model shows an average stable rate of salinity during the 4 years investigation period.

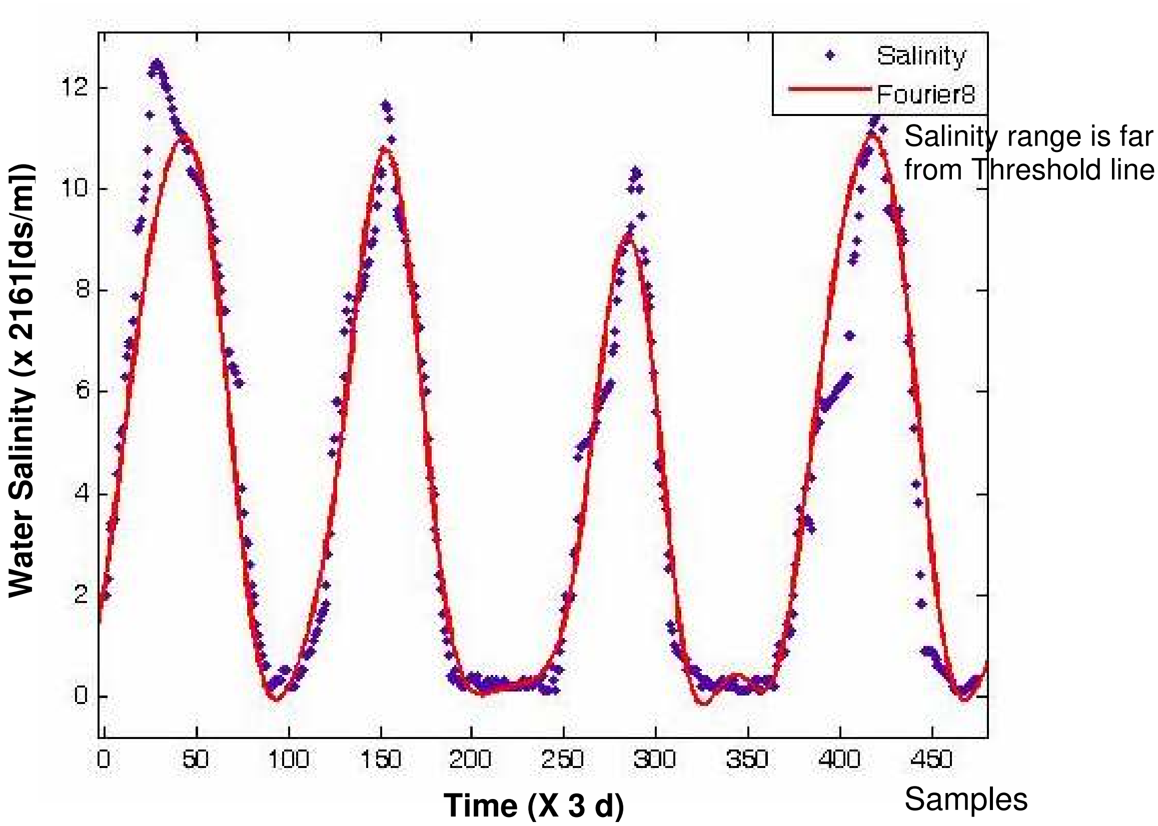


Figure 4.7 Fourier approximation of water salinity of Selagang-Harintana River

The highest salinity value is under the threashold line which is not harmful for plants growth and ecosystems.

4.4.4 Water salinity modelling of Sibsa - Nalianala River

Sibsa River is the second largest river in the Sundarbans region and it plays a vital role in communication and carrying fresh water from the upstream catchment. The Sibsa River is carry large volume of fresh water from the upstream Ganges and from other local sub-catchments and also from the important point where the fresh water and sea water mix together thereby balancing the coastal mangrove ecosystems. This is why this river water is moderate saline than other parts of river water salinity. The Passur is placed after the Meghna in size in the deltaic region. The river is joined with Mongla canal at about 32 km south of Chalna. Flowing further south, the river meets the Sibsa at about 32 km north of its mouth and debauches into the sea keeping its original name Passur. The river is very deep and navigable throughout the year and large marine ships can easily enter Mongla Sea Port through it. The

Passur is an important river route through which Khulna-Barisal steamboats and other vessels ply. The river is about 460m wide at Rupsa, about 790m at Bajuyan and about 2.44 km at the confluence of the Passur-Sibsa. The total length of the river is about 142 km. The Passur and all its distributaries are tidal channels. The Passur bifurcates into two at Mongla and the western branch flows through the Sundarbans as Sibsa River. The Sibsa has been renamed as the Kunga River near the estuary before joining the Bay of Bengal. Hiron Point is on the right-bank of the Sibsa-Kunga. The total length of the river is about 100 km. The river crosses about 27 km through Paikgachha upazila and the rest of the course demarcates the common boundary between Paikgachha and Dacope upazilas. Inside the Sundarbans, the Sibsa meets with the Passur and receives various rivulets and khals from various directions, enriching its flow. Among them the Barulia, Haria, Bunakhali, Garkhali, Mainas, Taki, Besekhali, Badurgachha, Bhelti, Karua Gamrail, Hadda and Nali Jalla are notable. The river experiences regular tides. Its water is saline throughout the year but at the high rate in the dry season and high salinity goes down in the rainy season of the year.

The reconstructed data was used to develop the Fourier polynomial model. The Fourier Model 8 (Figure 4.8) was considered as appropriate model. The Goodness of fit of the model, where the highest $r^2 = 0.9137$ and the lowest value of RMSE = 2.014, adjusted $r^2 = 0.9098$, Sum Square Error-SSE = 1529 and $\omega = 0.02861$. The Fourier polynomial approximation of 8^{th} order is given by the following equation; considering coefficients (with 95 % confidence bounds).

$$f(t) = 7.006 - 0.6134 \cos (0.02861 t) + 0.08996 \sin (0.02861 t) - 2.9 \cos (0.05722 t) + 7.997 \sin (0.05722 t) - 0.03639 \cos (0.08583 t) - 0.6724 \sin (0.08583 t) - 0.7276 \cos (0.11444 t) - 2.368 \sin (0.08583 t) - 0.2382 \cos (0.14305 t) + 0.5227 \sin (0.14305 t) + 0.221 \cos (0.17166 t) + 0.9901 \sin (0.17166 t) + 0.08443 \cos (0.20027 t) - 0.7531 \sin (0.20027 t) - 0.2139 \cos (0.22888 t) - 0.62 \sin (0.22888 t)$$

The Fourier polynomial model 8 was fit for the Sibsa-Nalianala River as an appropriate model considering the best approximation. In this model the graph is shows the dry season (February-June) highest salinity value 34576 dS/m in 2000, 36737dS/m in 2001, 43220 dS/m in 2002 and 47542 dS/m in 2003. The Fourier polynomial model shows the yearly increasing behaviour of water salinity in the Sibsa-Nalianala River. The first two years behaviour in increasing slowly, during 3^{rd} and 4^{th} years increasing rate is much faster than previous years.

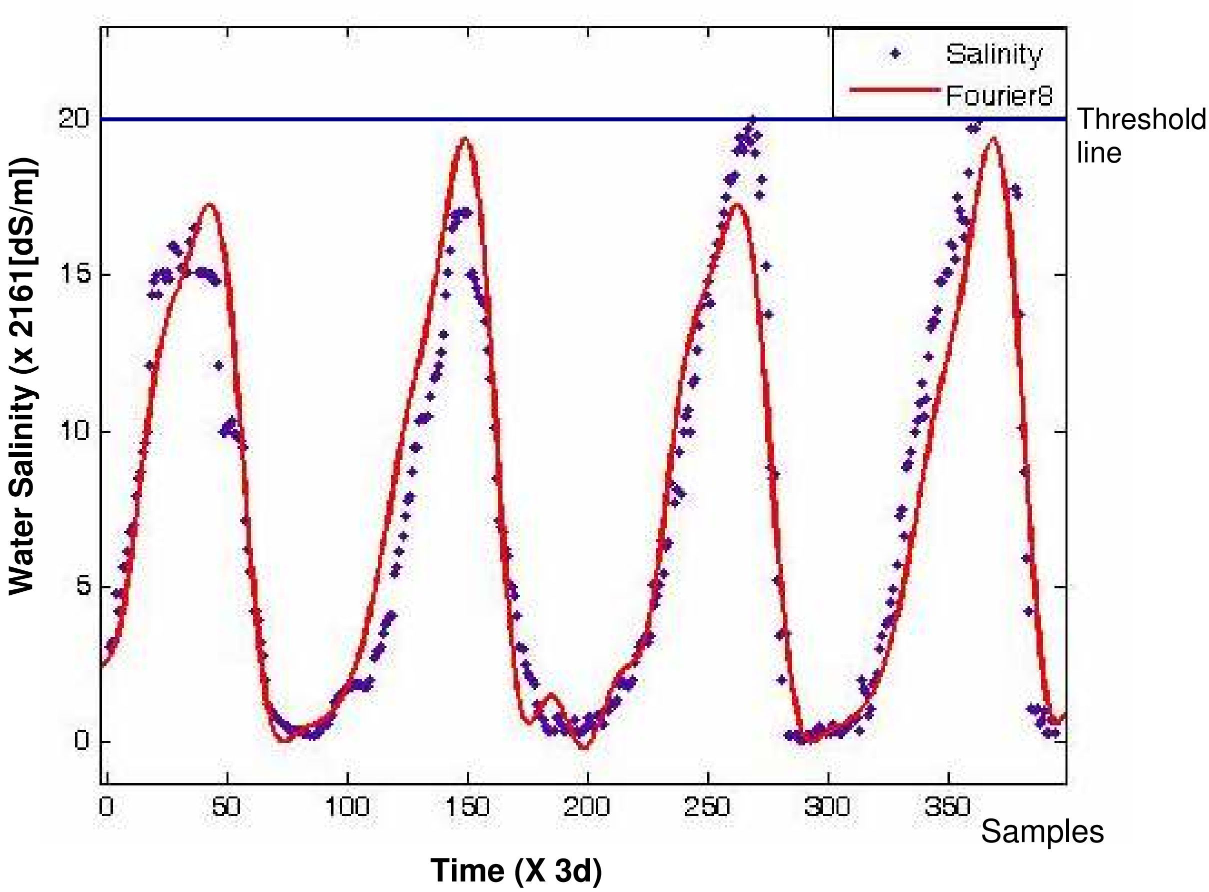


Figure 4.8 Fourier approximation of water salinity of Sibsa-Nalianala River

The last two years salinity increasing rate is in the marginal level of threshold line.

4.4.5 Water salinity modelling of Bal - Jhalia River

The Bal-Jhalia River is one of the medium largest rivers in the Sundarbans which is located in the southwestern portion of the forest wetlands. It also supply freshwater from the upstream local catchment. The Kobadak and Kholpetua Rivers are carry fresh water from the local catchment and joined with Bal-Jhalia River in the downstream area. Later on, it joined with the Arpongacia River which is potential river in the southwestern part in the Sundarbans.

After the data reconstruction of the Bal-Jhalia River it was used to develop the Fourier polynomial model. From all the models considered, Fourier model 8 (Figure 4.9) was considered as appropriate model. In the model the highest $r^2 = 0.6325$, adjusted $r^2 = 0.6002$ and the lowest value of Root Mean Square Error-RMSE = 4.508, Sum Square Error-SSE = 3923 and $\omega = 0.08369$, which is made the model as the best approximation. The Fourier polynomial approximation of 8th order is given by the following equation. Considering coefficients (with 95% confidence bounds):

$$f(t) = 16 - 1.293\cos(0.08369\,t) + 7.477\sin(0.08369\,t) + 1.18\cos(0.16738\,t) - 0.9296\sin(0.16738\,t) - 0.1423\cos(0.25107\,t) - 1.014\sin(0.25107\,t) - 0.2036\cos(0.33476\,t) - 0.6092\sin(0.33476\,t) + 0.3222\cos(0.41845\,t) - 0.3107\sin(0.41845\,t) + 0.1287\cos(0.50214\,t) - 0.4723\sin(0.50214\,t) + 0.09246\cos(0.58582\,t) - 0.3357\sin(0.58583\,t) + 0.4067\cos(0.6695\,t) - 0.2137\sin(0.66952\,t)$$

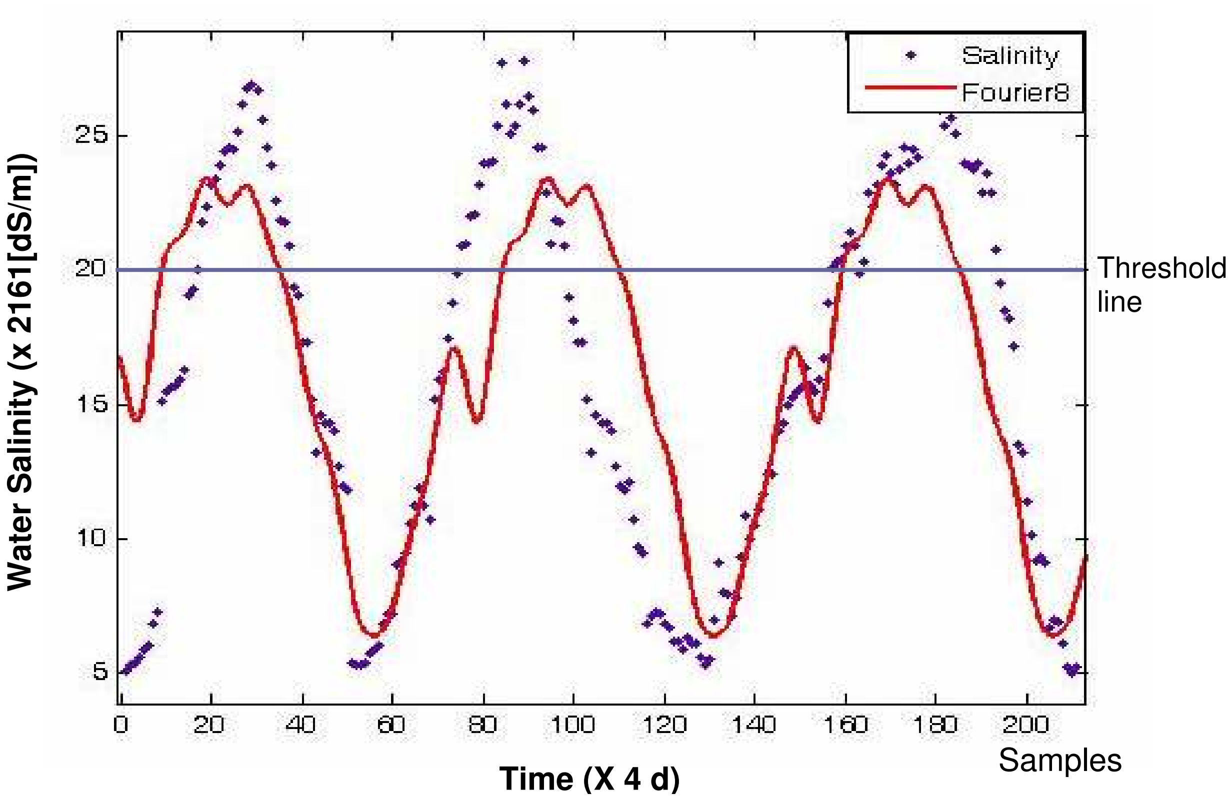


Figure 4.9 Fourier approximation of water salinity of Bal-Jhalia River

The Fourier polynomial model 8 (Figure 4.9) was fit for the Bal-Jhalia River as an appropriate model considering the best approximation. In this model the graph is shows the dry season (February-June) as the highest salinity value of 56186 dS/m in 2001, 57266.5 dS/m in 2002 and 60508 dS/m in 2003. The Fourier polynomial model shows the increasing rate of water salinity in the Bal-Jhalia River which is higher than the salinity threshold value.

4.4.6 Water salinity modelling of Passur - Passakhali River

Sibsa River and Passur River joined the downstream of the Sundarbans reserve forest at Passakhali location. The place where three rivers meet is called Passur-Passakhali River, and it converges with the Bay of Bengal. The tidal saltwaters mix with the upstream fresh water and eventually they enter at different part of the Sundarbans part of the wetlands. It is also a large estuary in the south portion of the Sundarbans.

After the data reconstruction and rearrangement of the Passur-Passakhali River, it was used to develop the Fourier polynomial model. Fourier model 6 (Figure 4.10) was considered as appropriate model for river Passur-Passakhali. In the model the highest $r^2 = 0.9452$, adjusted $r^2 = 0.9352$, Sum Square Error-SSE = 1152 and the lowest value of Root Mean Square Error-RMSE was found 1.735 and $\omega = 0.02719$, which made the model as the best approximation. Fourier polynomial approximation 6^{th} order is given by the following equation; considering coefficients (with 95% confidence bounds):

$$f(t) = 8.175 - 8.997 \cos(0.02719\,t) + 3.081 \sin(0.02719\,t) + 2.53 \cos(0.05438\,t) + \sin(0.05438\,t) - 0.2594 \cos(0.08157\,t) - 1.719 \sin(0.08157\,t) - 0.5761 \cos(0.10876\,t) + 0.5885 \sin(0.10876\,t) + 0.6313 \cos(0.13595\,t) + 0.4526 \sin(0.13595\,t) + 0.0654 \cos(0.16314\,t) - 0.4682 \sin(0.16314\,t)$$

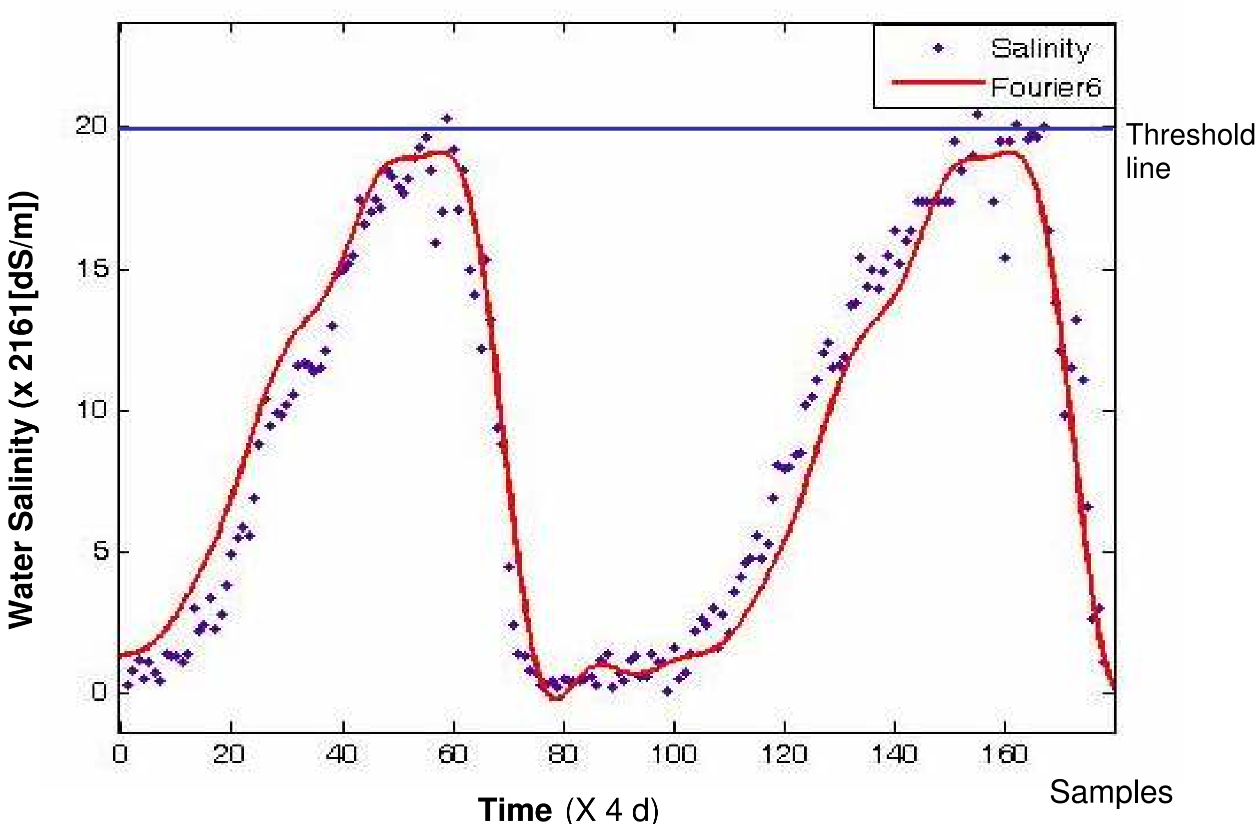


Figure 4.10 Fourier approximation of water salinity of Passur-Passakhali River

The Fourier polynomial model 6 was fit for the Passur-Passakhali River as appropriate model considering the best approximation. The graph shows that, the dry season (February-June) was the highest salinity of 43220 dS/m in 2002, 60508 dS/m in 2003. The Fourier polynomial model shows the yearly salinity increasing rate which is in the marginal level.

4.4.7 Water salinity modelling of Betmergang - Kathka River

The Bethmargang-Kathka River is made of two seperate rivers in the southeastern corner of the Sundarbans forest. The Kathka region is important area in the forest, it is also wildlife sanctuary which is called Sundarbans east sanctuary and the total area is 192 km^2. It is also popular wildlife sanctuary for the tourist attraction. All these avtivities includes the economic and environmental importance of the sanctuary consideration. The Betmargang and Khathka canal is play a vital role in communication and carrying fresh water from the Baleswar River and also from other connected rivers such as Selagang, Tambalbunia and Nandabala. The Baleswar River is carrys high volume of fresh water from the upstream Ganges and from other local subcatchments. The Bethmargang is the important point where the fresh water and the sea water mixing and balancing the coastal mangrove ecosystems. This is why this river water has very less saline compare to other rivers. In general the river water salinity is lower but in the dry season increase a little.

After the data reconstruction and rearrangement of the Betmargang-Kathka River it was used to develop the Fourier polynomial models. The Fourier model 2 (Figure 4.11) was considered as appropriate model for this river. The figure 4.11 shows the salinity increasing behaviour which has been adjusted with the Fourier polynomial model 2nd order. In the model the goodness of fit which is the highest r^2 = 0.8641, adjusted r^2 = 0.864 and the lowest value of Root Mean Square Error-RMSE = 2.118, Sum Square Error–SSE value is 5.727, and ω = 0.001423, which made the model as the best approximation. The Fourier polynomial approximation 2nd order is given by the following equation. Considering coefficients (with 95% confidence bounds):

$$f(t) = 9.364 - 7.662 \cos(0.001423\, t) - 0.2799 \sin(0.001423\, t) - 0.1035 \cos(0.002846\, t) + 0.479 \sin(0.002846\, t)$$

The Fourier polynomial model 2 was the best appropriate model for the Betmargang-Kathka River, where model is considering as the best approximation.

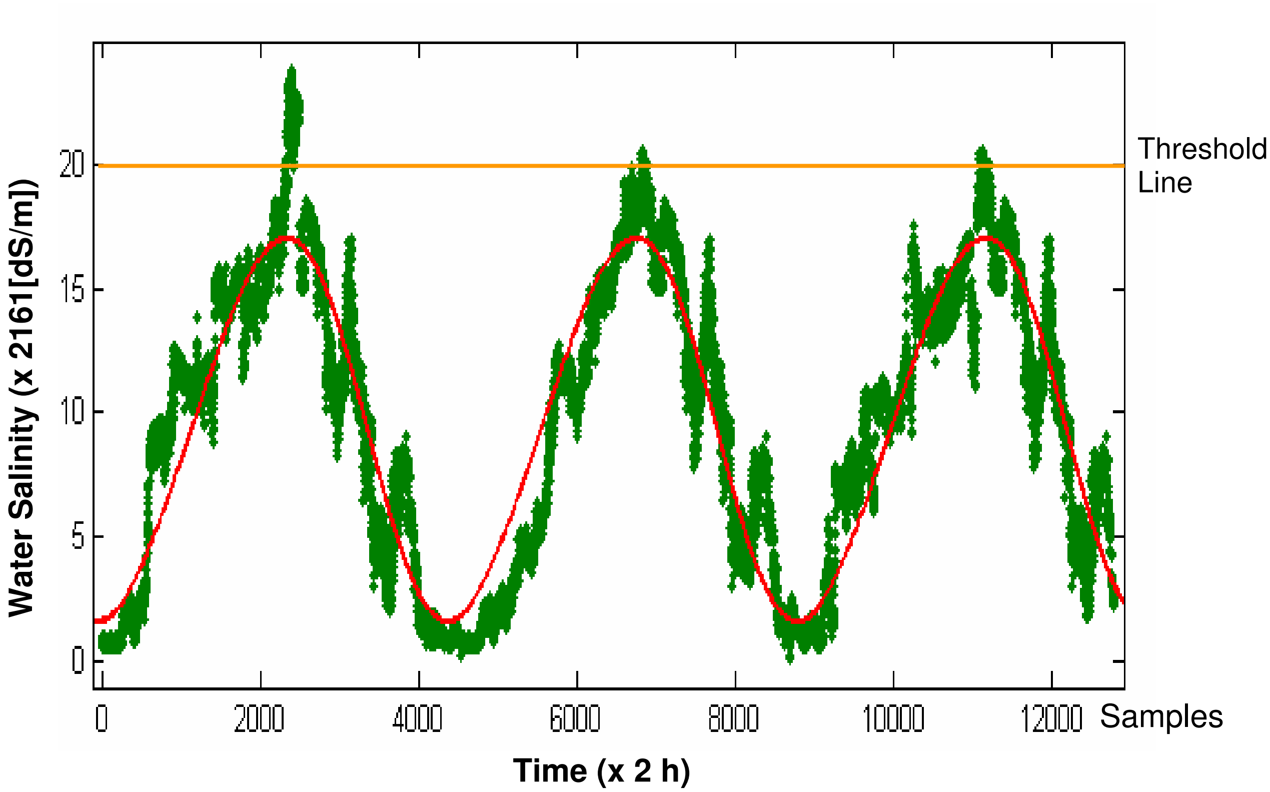


Figure 4.11 Fourier approximation of water salinity of Betmargang -Kathka River

In this model the graph (Figure 4.11) shows the dry season (February-June) scenarios with the heighest salinity value which is 51864 dS/m in 2001, 43220 dS/m in 2002 and 49703 dS/m in 2003. The Fourier polynomial graph shows the yearly salinity fracturing behaviour which is totally depending on the availability of fresh water supply in the river basin area of the Sundarbans.

4.4.8 Water salinity modelling of Chunar - Munchiganj River

The Chunar-Munchiganj River is one of the smaller but important rivers in the southwestern part of Bangladesh especially in the northern boundary of the Sundarbans. The Chunar-Munchiganj River is serving as a boundary between the Sundarbans mangrove wetlands and the northern settlements areas of the Indian boarder towards Munchiganj town. The river is important for local communication and a fertile water shade for shrimp prawn collection. The river connected with Kanksially River and Kalindi River which is one of the transboundary rivers in the Sundarbans forest area. After the Chunar-Munchiganj River enters the Sundarbans, it is renamed as Malancha and it joins with Ichamati River when it enters into the Sundarbans. The upstream fresh water from the local catchment is flows into the Chunar-Munchiganj River. But recently the situation changed there is no enough fresh water from the upstream, whereas the Chunar-Munchiganj Rriver's water is used in the shrimpfield, in the northern boundary of the Sundarbans. For various reason water and soil salinity has been drastically increased in the Chunar- Munchiganj basin area. The salinity rate is increasing gradually.

After the data reconstruction and rearrangement of the Chunar-Munchgnj River it was used to develop the Fourier polynomial models. The Fourier model 8 (Figure 4.12) was considered as appropriate model for this river. In the model the highest $r^2 = 0.955$, adjusted $r^2 = 0.9528$ and the lowest value of Root Mean Square Error-RMSE = 1.231 and $\omega = 0.01985$, which has made the model as the best approximation.The Fourier polynomial approximation 8^{th} order is given by the following equation ; considering coefficients (with 95% confidence bounds):

$$f(t) = 13.59 + 2.099 \cos(0.01985\,t) + 0.82 \sin(0.01985\,t) - 0.7342 \cos(0.0397\,t) - 0.2323 \sin(0.0397\,t) - 2.657 \cos(0.05955\,t) + 6.032 \sin(0.05955\,t) - 1.318 \cos(0.0794\,t) + 1.013 \sin(0.0794\,t) + 0.732 \cos(0.09925\,t) - 0.4589 \sin(0.09925\,t) - 0.4179 \cos(0.1191\,t) - 1.682 \sin(0.1191\,t) + 0.8124 \cos(0.13895\,t) - 0.2593 \sin(0.13895\,t) - 0.09655 \cos(0.1588\,t) + 0.5521 \sin(0.1588\,t)$$

The Fourier polynomial model-8 was fit in the Chunar-Munchiganj River as appropriate model considering the best approximation. The figure 4.12 shows the Fourier polynomial model order 8^{th} where the water salinity cyclic behaviour has been seen. In this model the graph shows the dry season (February-June) average highest salinity value which is 54025 dS/m in 2000, 49703 dS/m in 2001 and 54025 dS/m in 2002 and 56186 dS/m in 2003. The time serioes consideration of the water salinity intrusion of Chunar-Munchiganj River is a cyclic increasing behaviour. This is indicating the future increasing trend of water salinity in this river in the Munchiganj region.

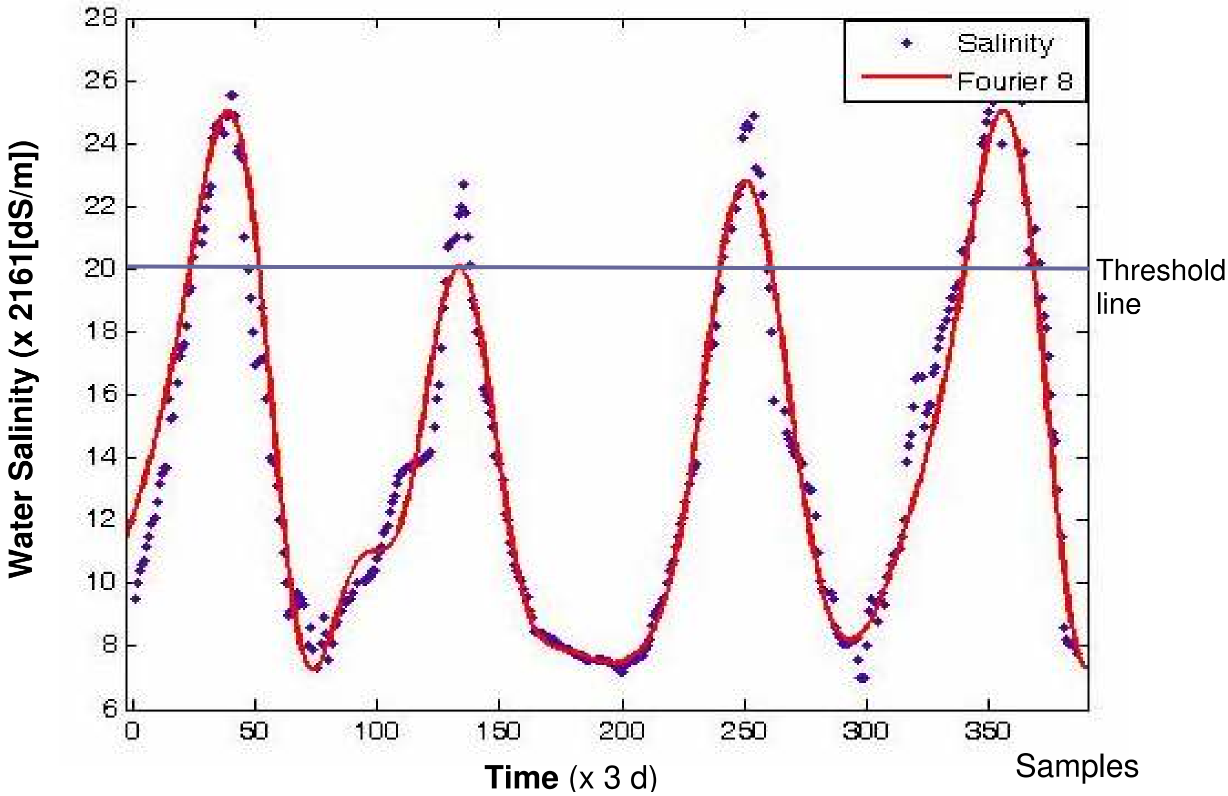


Figure 4.12 Fourier approximation of water salinity of Chunar-Munchiganj River

The Fourier polynomial model graph shows the yearly salinity increasing behaviour, after 2000 the salinity rate was 54025 dS/m, suddenly in thefollowing year, the rate decreased at 49703 dS/m and again 54025 dS/m in 2002. The reason was that in March-April of 2001 there was early raining and some water flows from the local catchment.

4.4.9 Water salinity modelling of Kholpetua - Kobadak River

The kobadak and Kholpetua Rivers are the biggest rivers in the Sundarbans region. The Kholpetua-Kobadak River plays an important role in supply of fresh water from upstream area and from the local catchment. Kobadak and Kholpetua Rivers are connected with Arpongachia and Bal River. The Bal-Jhalia and Arpongachia joins with Malancha River further downstream. Arpongachia and Malancha are connected to Bhairab by Kobadak River and used to receive some amount freshwater flow from the Ganges through the Gorai River. These two rivers have a connecting role inside the Sundarbans and in the boundary area of the Sundarbans. The basin area now is becoming important for shrimp cultivation and other mangrove resource related commercial activities. Surrounding this river catchment is the agricultural lands, which is being converted into shrimp farms where as the high saline water is also important issue to farmers and attract shrimp business people. It is very important for shrimp farming and also it carrys fresh water into the south-west part of the Sundarbans for balance the mangrove wetlands ecosystems.

After collected, checked and rearrangement of salinity data of the Kholpetua-Kobadak Rivers was used to develop the Fourier polynomial models. The Fourier model 8 (Figure 4.13) was considered as appropriate model for this river. In the model the highest r^2 value was 0.839, adjusted r^2 value was 0.8323, Sum Square Error-SSE = 2585, the lowest value of Root Mean Square Error-RMSE was 2.511 and $\omega = 0.02258$. These impressive results made the model as the best approximation. The Fourier polynomial approximation 8^{th} order is given by the following equation; considering coefficients (with 95 % confidence bounds).

$$f(t) = 13.43 - 0.04756 \cos(0.02258\,t) - 0.3776 \sin(0.02258\,t) - 2.958 \cos(0.04516\,t) - 7.35 \sin(0.04516\,t) - 0.844 \cos(0.06774\,t) - 0.05306 \sin(0.06774\,t) - 1.341 \cos(0.09032\,t) + 0.2829 \sin(0.09032\,t) - 0.03563 \cos(0.1129\,t) + 0.5077 \sin(0.1129\,t) + 0.1307 \cos(0.13548\,t) + 0.5077 \sin(0.13548\,t) + 0.08059 \cos(0.15806\,t) - 0.1235 \sin(0.15806\,t) + 0.2368 \cos(0.18064\,t) - 0.2988 \sin(0.18064\,t)$$

The Fourier polynomial model 8 was fit for the Kholpetua-Kobadak River as appropriate model consideration with best approximation. In this model the graph is shows the dry season (February-June) gives the highest salinity value which is 38898 dS/m in 2001, 47542 dS/m in 2002 and 54025 dS/m in 2003. The time series data consideration of this river the water salinity increasing behaviour is forcasting the future increasing trend of water salinity in this reiver. The Fourier polynomial model of water salinity order 8^{th} shows the appropriate salinity situation of this river.

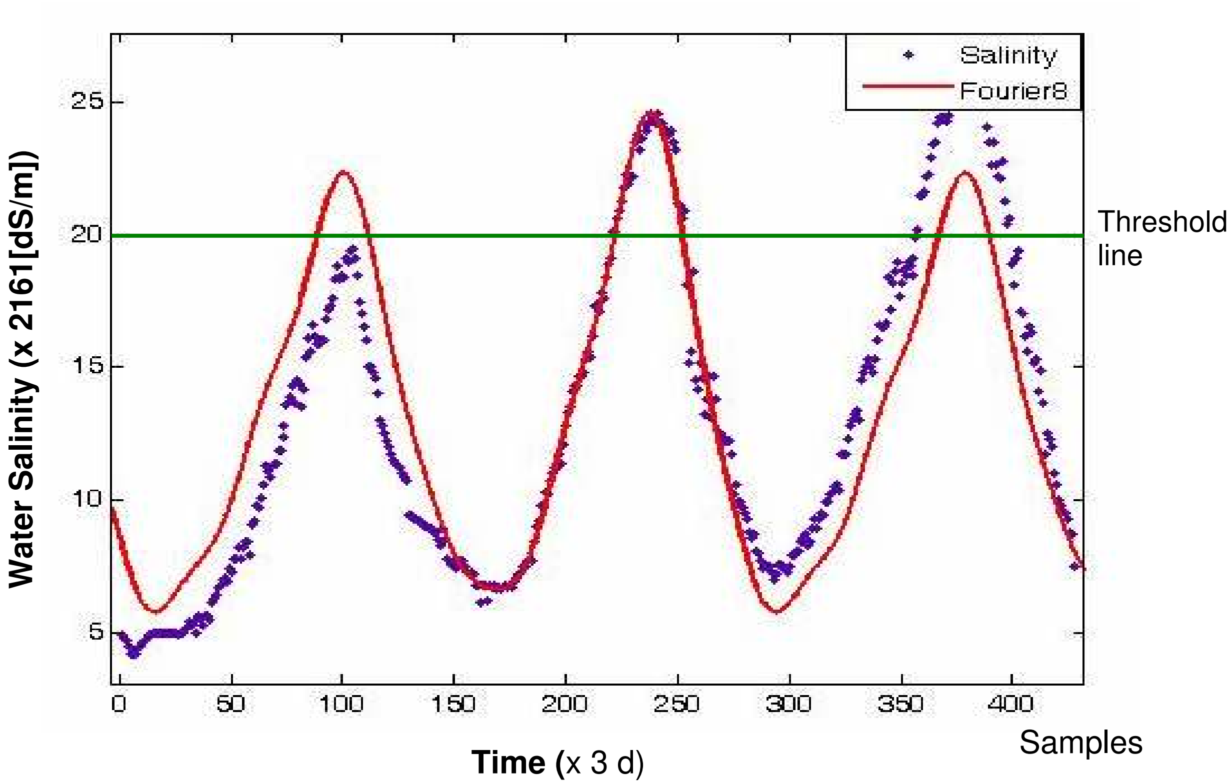


Figure 4.13 Fourier approximation of water salinity of Kholpetua-Kobadak River

The Fourier polynomial model graph shows the yearly salinity increasing behaviour which has already crossed the threshold line in the particular river location.

4.4.10 Water salinity modelling of Notabaki khal - Notabaki River

The Notabakikhal-Notabaki River is located at the southwestern area of the Sundarbans. The Kalindi-Kaikhali River join with Jamuan-Dingimari River and a branch of Deboki River in the western side with Jamuna River and its name become Jamuna-Dingimari and it continues flowing downstream. The turning point of the river is called Notabaki, and it becomes wider in this region. Some small creeks and canals also join this Notabaki point. The River flows downstream and it is as one of the biggest rivers in the western Raimangal estuary. Finally the river Notabaki joins with Raimangal and eventually joins Sea. In genreal this river and estuary are in the western part and is classified as the western part of the moribund delta while estuaries of the eastern part are the part of active delta. This western part river is strongly influenced by tides. So the salinity density is also influenced by tide and sea surface water salinity. There are some fundamental reasons for high salinity in the coastal surface water in the Bay of Bengal. So the water sample collection from this point is important and it will carry some fundamental and basic result of water salinity in the Sundarbans rivers, which will play a vital role in the function of ecosystems in the coastal Sundarbans.

After reconstruction and rearrangement of the data of the Notabakikhal-Notabaki River it was used to develop the Fourier polynomial models. The Fourier model 2 (Figure 4.14) was considered as appropriate model for this river. In the model the highest r^2 value is 0.9489, adjusted r^2 value is 0.9481 and the lowest value of Root Mean Square Error-RMSE = 1.478, Sum Square Error-SSE = 738 and ω = 0.05211 which made the model as the best approximation. The Fourier polynomial approximation 2^{nd} order is given by the following equation; with consideration of coefficients (with 95% confidence bounds).

$$f(x) = 17.21 - 8.056 \cos(0.5211t) + 4.008 \sin(t\ 0.05211) + 1.277 \cos(t\ 0.10422) + 0.4013 \sin(0.10422\ t)$$

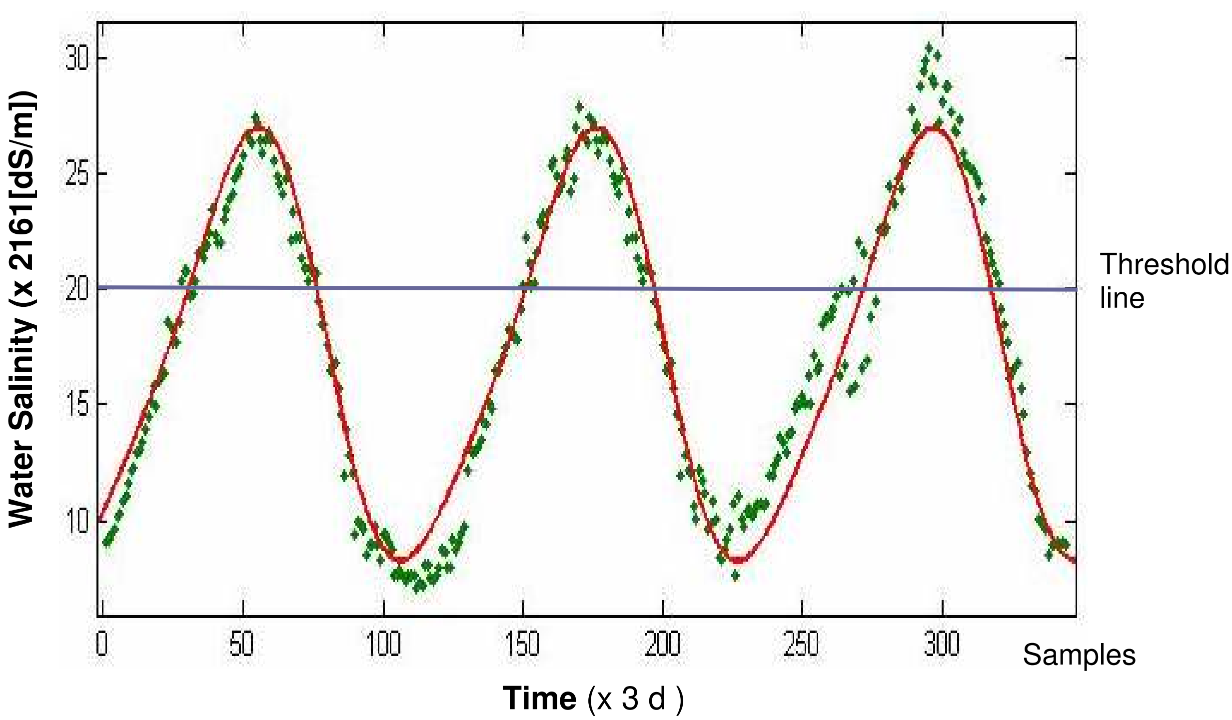


Figure 4.14 Fourier approximation of water salinity of Notabakikhal-Notabaki River

The Fourier polynomial model 8 was fit (Figure 4.14) for water salinity model in the Notabakikhal-Notabaki River as appropriate model, considering its best approximation. In this model the graph is shows the dry season (February-June) with the highest salinity value which is 51864 dS/m in 2001, 56186 dS/m in 2002 and 64830 dS/m in 2003. The Fourier polynomial model graph shows the yearly salinity increasing behaviour.

4.4.11 Water salinity modelling of Arpongasia - Deboki River

Arpongasia-Deboki is one of the major rivers in the south western region of Sundarbans. It is situated in the southwestern part of the Sundarbans and carrys fresh water from the upstream of south-western rivers and from sub catchments in the country. There are river networks within the local and international rivers. All the rivers, canals and creeks entered the reserve forest and some cases these small rivers join at important point of major rivers. The Kabodak River and Kholpetua Rivers join at a point, after which it is called where the Kholpetua-kabadak Rriver and it continues to flow downwards and join Arpongasia aand Bal-Jhalia Rivers. At this point the rivers called Arpongasia-Deboki River. Time seris data from this point were collected. This point is important for different reasons, it is the middle point of the region of river net work and combind flows of important rivers and it is also closer to the boundary of the sea boarder where every day a tidal wave influences are available.

After rearrangement of the data of the Arpongasia-Deboki River it was used to develop the Fourier polynomial models. The Fourier model 4 (Figure 4.15) was considered as appropriate model for this river. The figure 4.15 shows the practical situation of water salinity of this river which is forcasting the future trends. In the model the highest r^2 value is 0.8884, adjusted r^2 value is 0.8713, the lowest value of Root Mean Square Error-RMSE was 2.635, Sum Square Error-SSE is found 1119 and ω = 0.0654 which imade the model as the best approximation. The Fourier polynomial approximation 4^{th} order is given by the following equation; Consideration of coefficients (with 95% confidence bounds):

$$f(t) = 16.09 - 3.225 \cos(0.0654\, t) + 9.258 \sin(0.0654\, t) + 0.9156 \cos(0.1308\, t) - 2.373 \sin(0.1308\, t) - 0.07958 \cos(0.0654\, t) - 0.4234 \sin(0.0654\, t) - 0.5269 \cos(0.2616\, t) + 0.01945 \sin(0.2616\, t)$$

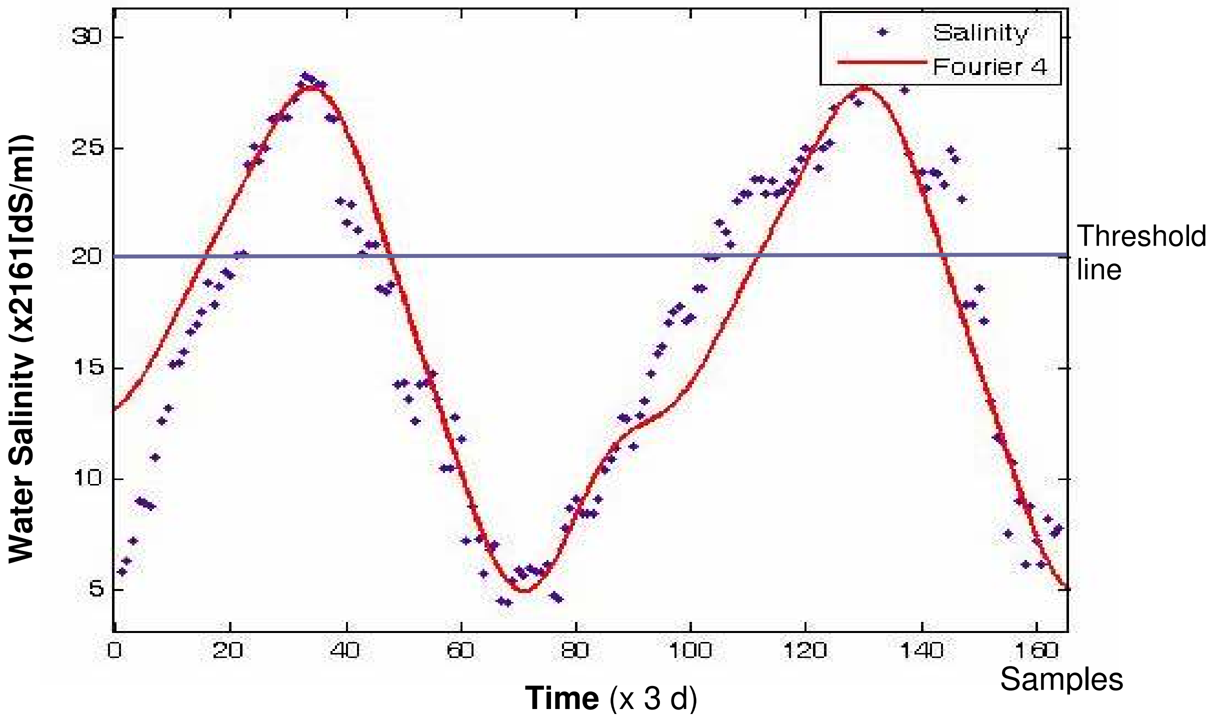


Figure 4.15 Fourier approximation of water salinity of Arpongasia-Deboki River

Fourier polynomial model 4 was developed using MATLAB version 7.1 software. The Fourier polynomial model shows the river water salinity behaviur in the graph. The graph shows the dry season salinity of 60508 dS/m in 2002 and 64830 dS/m in 2003. The Model shows the salinity increasing behaviour in the Arpongasia-Deboki River. Both years dry season salinity crossed the threshold line of water salinity in this river basin.

4.4.12 Water salinity modelling of Nilkamal - Hironpoint River

The biggest river in the Sundarbans by name Passur enters at Nilkamal-Hironpoint area and is situated at the south of the Sundarbans where rivers and sea meet. Hironpoint is very important spot for the Sundarbans and also for the whole region. From the upstream the two majors' rivers called Passur and Sibsa River the place called Passur Passakhali and the river became a wide river here. At this area, the river name is Passur Passakhali. It is flowing upto Hironpoint by name Passur that make it the wider river in the Sundarbans region. Actually it is very difficult to recognise the length of the river before it joins the sea. At the mouth of Passur River and this area, the river's width is 10 km to 20 km some time. The sea saline water are enter from this point, all the ships from outside and from the deep sea are enter this point, the

Hironpoint is the administrative point and office of the Mongla sea port. The salinity rate of Nilkamal-Hironpoint River is normally higher than other region in Sundarbans. Salinity rate also can be lower, depending on the fresh water carring capacity from upstream by the two major rivers namely Passur and Sibsa.

The reconstructed data of the Nilkamal-Hironpoint River it was used to develop the Fourier polynomial models. The Fourier model 8 (Figure 4.16) has considered as appropriate model for this river. In the model the highest r^2 value is 0.9802, adjusted r^2 value is 0.9802, the lowest value of Root Mean Square Error-RMSE = 1.086, Sum Square Error-SSE = 1.494 and ω = 1.13 which made the model as the best approximation. The Fourier polynomial approximation 8th order is given by the following equation; considering coefficients (with 95% confidence bounds).

$$
\begin{aligned}
f(t) = & -263.2 + 519.5 \cos(1.13\,t) - 62.65 \sin(1.13\,t) \\
& - 426.9 \cos(2.26\,t) + 105.9 \sin(2.26\,t) + 304 \cos(3.39\,t) - 119.9 \sin(3.39\,t) \\
& - 181.8 \cos(4.52\,t) + 105.5 \sin(4.52\,t) + 102.8 \cos(5.65\,t) - 77.47 \sin(5.65\,t) \\
& - 38.89 \cos(6.78\,t) + 44.74 \sin(6.78\,t) + 10.7 \cos(7.91\,t) - 20.79 \sin(7.91\,t) \\
& - 1.193 \cos(9.04\,t) + 6.423 \sin(9.04\,t)
\end{aligned}
$$

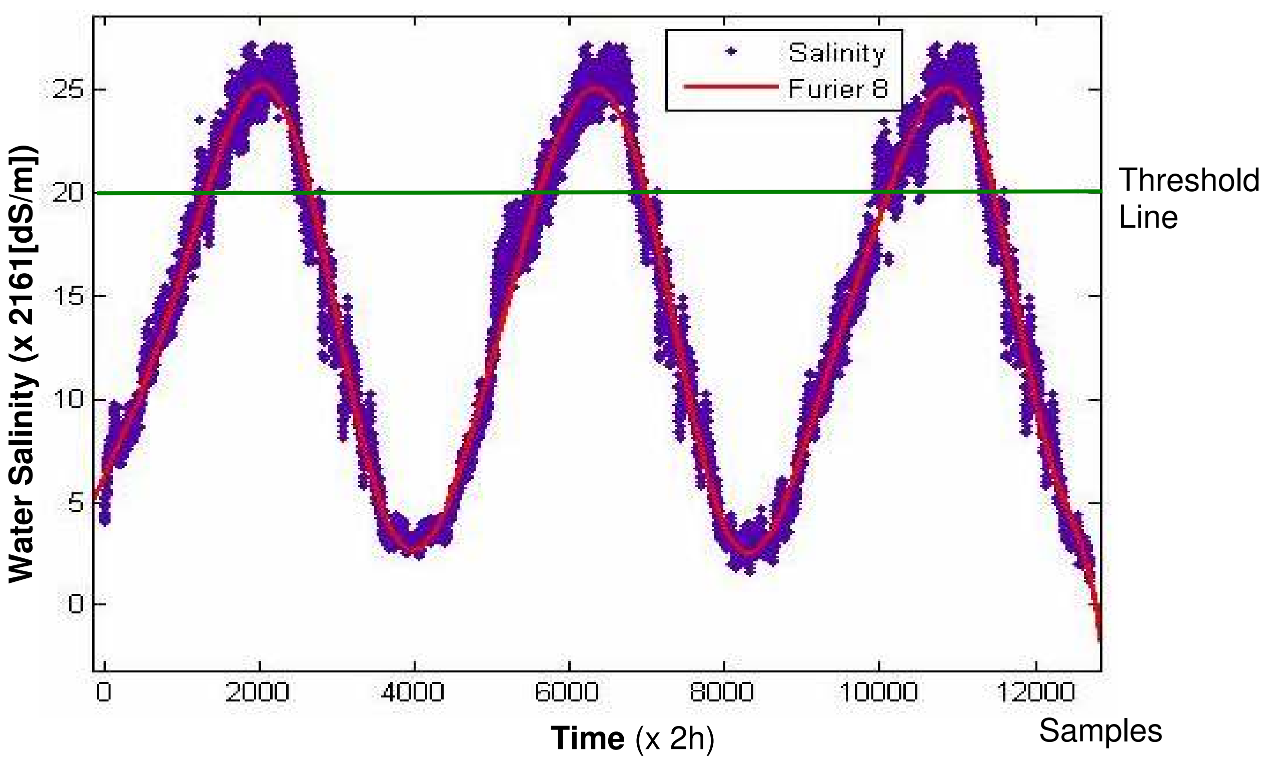


Figure 4.16 Fourier approximation of water salinity of Nilkamal-Hironpoint River

Fourier polynomial model 4 was developed using the MATLAB version 7.1 software. The Fourier polynomial model shows the cycling water salinity behaviur. The graph shows the dry season salinity, the average dry season water salinity is 56186 dS/m in 2001, 60508 dS/m in 2002 and 62669 dS/m in 2003. The Model shows the yearly cycling salinity increasing behaviour in the Nilkamal-Hironpoint River basin it crossed the threshold line. The water of Nilkamal river basin is harmful for mangrove ecosystems.

4.4.13 Water salinity modelling of Malancha - Mandarbaria River

The Malancha-Mandarbaria is the largest river interms of width in the southwestern corner in the Sundarbans mangrove forest area. Before it enters the Sundarbans, the Malancha River known as Chunar River it joins with Ischamoti River before it enters into the Sundarbans forest near the Kodamtala station. From the eastern side of Kobadak River, it enters the Sundarbans and rename as Arpongasia River in the downstream. Arpongasia River is later connected with Bival River and rename as Bara Panga River, finally Bara Panga River is connected to Malancha River. At this point, Mandarbaria and Malancha became large in width, in the south and finally it is connected with Bay of Bengal. Mandarbaria is the last land before Bey of Bengal. Hariabhanga River is located just after the west corner of Mandarbaria and it is an inter boundary river. Malancha is one of the largest estuaries in the south west of the Sundarbans which is playing an important role in increasing the water salinity and balance ecosystems in the coastal region. The salinity rate of Malancha-Mandarbaria River is normally higher than other region in the Sundarbans. Salinity rate also can be lower depending on fresh water carrying capacity from upstream local catchment. Saline water of Bay of Bengal enters the Sundarbans through this river basin and channels. It is very important place for saline water samples collection to realise the salinity situation in the whole Sundarbans region and compare with other important places in the forest.

All the data was checked very carefully and after reconstruction and rearrangement of the data of the Malancha-Mandarbaria River it was used for time series model. In the case of Malancha-Mandarbaria River the general Fourier model 2 (Figure 4.17) was considered as appropriate model. In the model the goodness of fit where the highest r^2 value is 0.9424, adjusted r^2 value is 0.9423, the lowest value of Root Mean Square Error-RMSE = 1.881, Sum Square Error-SSE = 4.624 and ω = 0.001464 which made the model as the best approximation. The Fourier polynomial approximation 2nd order is given by the following equation; with coefficients (with 95% confidence bounds).

$$f(t) = 18.13 - 10.5 \cos(0.001464\ t) - 0.935 \sin(0.001464\ t) - 1.316 \cos(0.002928\ t) + 0.8043 \sin(0.002928\ t)$$

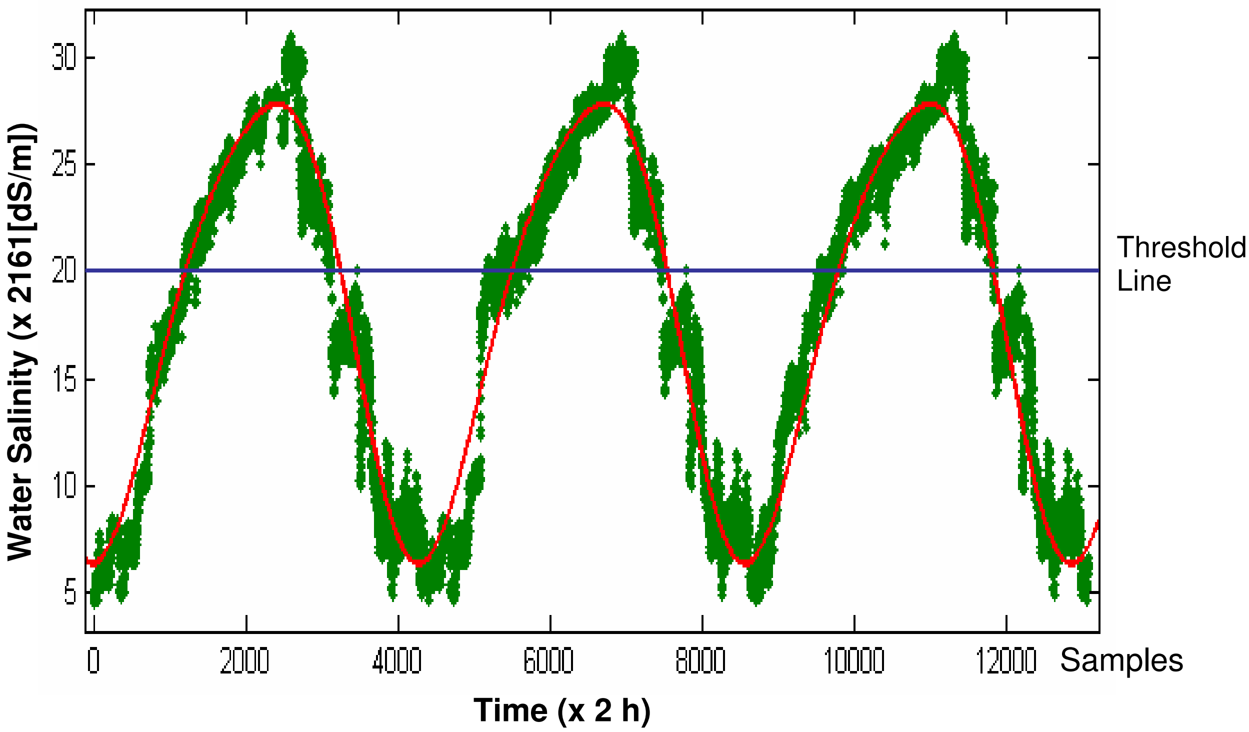


Figure 4.17 Fourier approximation of water salinity of Malancha-Mandarbaria River

The Fourier polynomial model 2 has been accepted as water salinity model in the Malancha-Mandarbaria river as appropriate model consideration with best approximation. In this model the graph is showing the dry season (February-June) average highest salinity value which is 60508 dS/m in 2001, 62669 dS/m in 2002 and 69152 dS/m in 2003. The Fourier polynomial model graph shows the yearly salinity increasing behaviour of the Malancha-Mandarbaria River. This is the most southern river in the Sundarbans region where the water salinity rate is always high.

4.5 Overall discussions

Modelling of water salinity in the Sundarbans Rivers is one of the vital issues for the protection of its mangrove ecosystems and the natural resources management. Considering the fragile environmental situation in the Sundarbans mangrove wetlands forest area it has been chosen as case studies. In the case area there are over 430 rivers and creeks flowing inside the forest and carry the fresh water (H_2O) from the upstream. Down to shortage of fresh water from upstream catchment the downstream rivers are loosing fresh water and the capillary way. Increasing sea salt water is the present threats to mangrove ecosystems in the case area. For understanding the real situation in the Sundarbans region 13 important rivers which are located around the case area have been chosen for modelling of their water salinity. The time series model is the tool which can display the real situation. For this reason the time series model has got the priority in my case analysis. The Fourier polynomial model is one of the acceptable appropriate approaches for water salinity modelling. In the Sundarbans case, I have selected 13 river basins and series salinity data has been collected. Fourier polynomial models have been developed based on the collective data. All the 13 rivers models show the water salinity increasing behaviour. In most of the rivers water salinity modelling showing the cycling behaviour and through this cycling behaviour it is possible to forecast the future situation. Most of the rivers models have been fit as Fourier polynomial model 8 and 2 which is the best approximation of models.

The Fourier polynomial models are showing the cycling behaviour where the peak values are recognisable from the model graphs. Analysing all the models result, it shows that Sundarbans wetland's salinity situation can be categorised into 2 directions such as east to west direction, south to north direction (Figure 4.19). The water salinity investigated results show that the salinity rate is much higher in the southern and south western rivers, the rivers of the middle area of the Sundarbans are moderate level and the rivers of the northern portion of Sundarbans carry low salinity rate salinity than the rivers of middle areas of the Sundarbans. Low salinity was found in the eastern river like in the Baleswar-Bogi river which is the only river in the Sundarbans region getting fresh water from Ganges and from others rivers, this is the reason why this area is still less saline zone where the forest and mangrove ecosystems are not harmful at all. Accordingly, the Selagang-Harintana River and Passur-Mongla rivers are carrying considerable rate of salinity which is not harmful for the mangrove wetland ecosystems within the Sundarbans site location. Considering the Fourier polynomial models on 13 rivers the following chart (Table 4.3) is showing the peak values of water salinity in the dry season (February-June).

Table 4. 3 Highest water salinity rates (dS/m) in river basins in the Sundarbans

River Basin	**2000** dS/m	**2001** dS/m	**2002** dS/m	**2003** dS/m	**Average** dS/m	**Remarks**
Basin - 1 Passur-Mongla	-	-	45381	51864	48622.5	Considerable
Basin - 2 Baleswar-Bogi	11885.5	10805	10805	10372.8	10956.27	Satisfactory
Basin-3 Selagang-Harintana	26364.2	25932	23771	25932	25499.8	Satisfactory
Basin - 4 Sibsa-Nalianala	34576	36737	43220	47542	40518.75	Considerable
Basin - 5 Bal-Jhalia	-	56186	58347	60508	58347	High salinity
Basin - 6 Passur-Passakhali	-	-	43220	60508	51864	High Salinity
Basin - 7 Betmargang-Kathka	-	51864	43220	49703	48255.13	Considerable
Basin - 8 Chunar-Munchiganj	54025	49703	54025	56186	53484.75	High salinity
Basin - 9 Kholpetua-Kobadak	-	38898	47542	54025	46807.26	Considerable
Basin - 10 Notabakikhal-Notabaki	-	51864	56186	64830	57612.26	High salinity
Basin - 11 Arpongasia-Deboki	-	-	60508	64830	62669	High salinity
Basin - 12 Nilkomal-Hironpoint	-	56186	60508	62669	59773.26	High salinity
Basin - 13 Malancha-Mandarbaria	-	60508	64830	69152	64830	High salinity
	Th - 1 R *U.Th* - 3R *Miss* - 9 R	*Th* - 6R *U.Th*- 4R *Miss*- 3R	*Th* - 8R *U.Th*- 2R *Mar* - 3R	*Th* - 11R *U.Th*- 2R		

(*Note:* Considering the time series model results of water salinity on 13 potential rivers have been categorized based on water salinity threshold value 43220 dS/m (20 ppt) is the threshold value which has been recognized before. Here *Th* - Threshold line, *U.Th* - Under threshold line, *Miss* - Missing data and information, *Mar* - Marginal value and R- River).

The result of Fourier polynomial model on 13 rivers in the Sundarbans region (Figure 4.18) are showing the following information like in 2000 there are only one river (Chunar-Munchiganj) has crossed the salinity threshold line (according to Clough in 1985, 43220 dS/m [20 ppt] which has been considered as maximum optimum range for the growth of major mangrove species). Three rivers water salinity still under threshold line and 9 rivers water salinity information is not available for the year 2000. Accordingly in 2001 the model results show that 6 rivers water salinity has crossed the threshold line, 4 rivers water salinity is under threshold line and 3 rivers information is missing. In 2002 the model results are showing the information that 8 rivers water salinity has crossed the threshold value, 2 rivers water salinity range under threshold line and 3 rivers water salinity in the marginal point. In 2003, the model results are demonstrating that 11 rivers water salinity has crossed the threshold value and only 2 rivers water salinity is under threshold line.

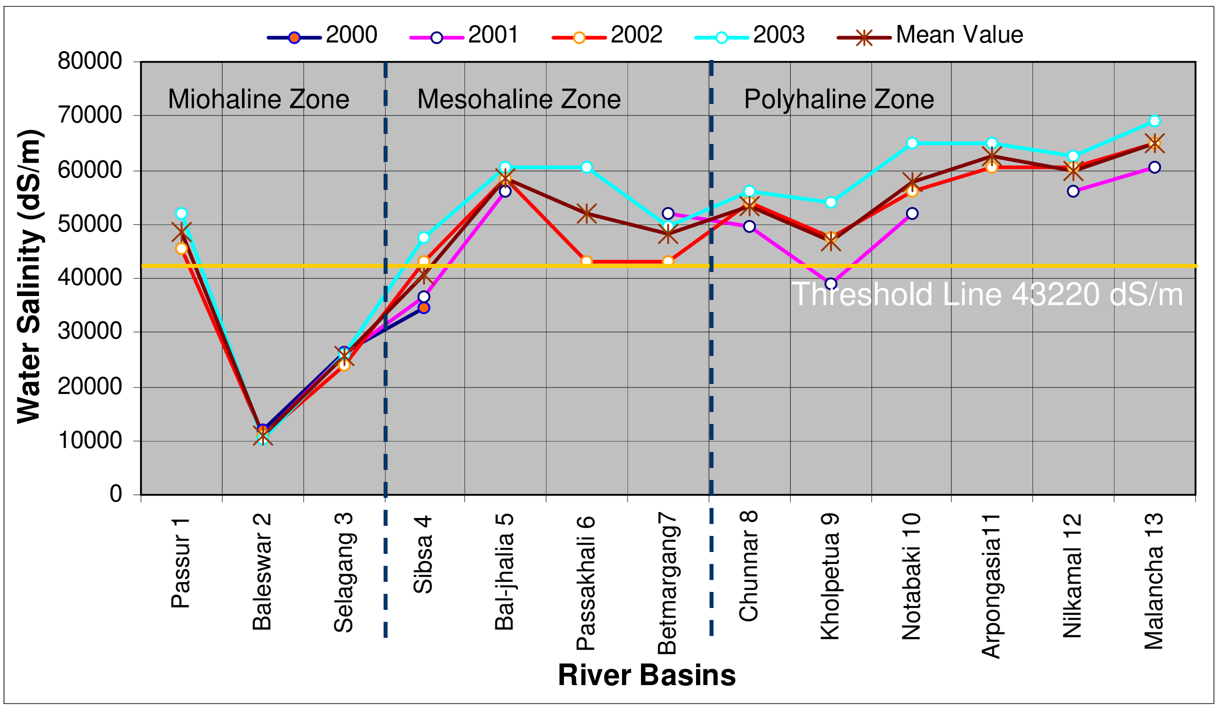


Figure 4.18 Result of water salinity modelling of the rivers in the Sundarbans

After analysis the result of Fourier polynomial models on 13 rivers (Figure 4.18) during 4 years time series basis, the result showing that only one river has crossed the threshold line in 2000, 6 rivers have crossed in 2001, 8 rivers have crossed in 2002 and 11 rivers have crossed in 2003. So the result show that the river water increasing rate is increasing gradually and more rivers are affected. Most of affected rivers are in the southern part and gradually in the middle part and lastly in the northern part, on the otherhand most of the rivers are located in the western part than in the middle part and the rivers of east part is less saline affected area.

The Figure 4.18 and Figure 4.19 shows the overall salinity increasing trends of the whole Sundarbans region. As a whole considering all the models results and the peak average three years values show the real scenarios on the Sundarbans salinity.

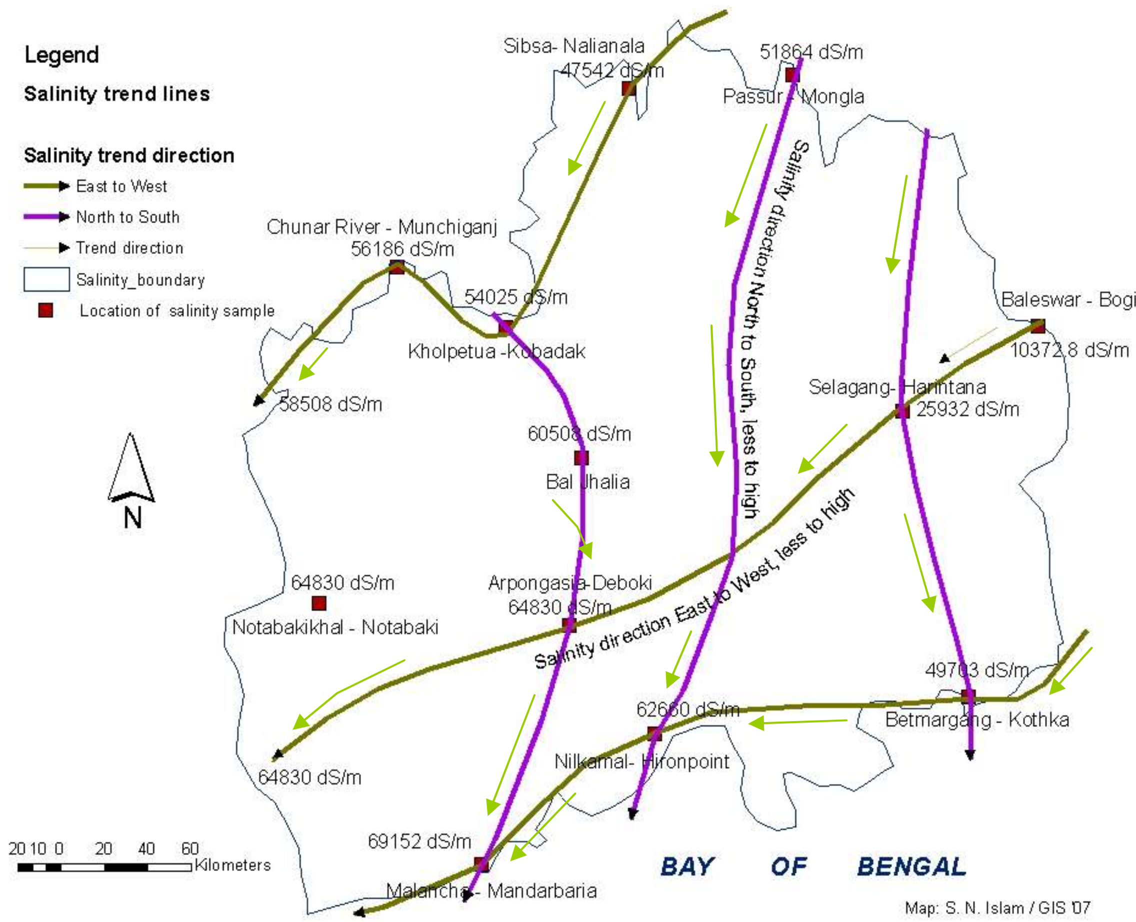


Figure 4.19 Salinity increasing in rivers water in different directions

The average peak values of water salinity, 4 rivers (basin 1, 2, 3 and 4) which are in good situation. Two rivers (basin 7 and 9) are carrying the moderate situation. There are 7 rivers (basin 5, 6, 7, 8, 10, 12 and 13) which are carrying the high salinity rate in the dry season which are the threats for mangrove ecosystems. The highset water salinity values are found at the Malancha-Mandarbaria River in the south and the straight north the Chunar-Munchiganj River is carrying the highest salinity value in the north side of Sundarbans (Figure 4.20). Simultaneously water salinity is increasing in the Kholpetua-Kobadak River which location is also in the northern boundary of the Sundarbans area. Surrounding these two rivers there are vast area of agricultural fields, shrimp cultivation farms, settlements and urban growth centres are located. If the salinity rate continuously increases in the future years then it will be a fragile threat for the cultural landscapes, agricultural crops and for the whole ecosystems of the region.

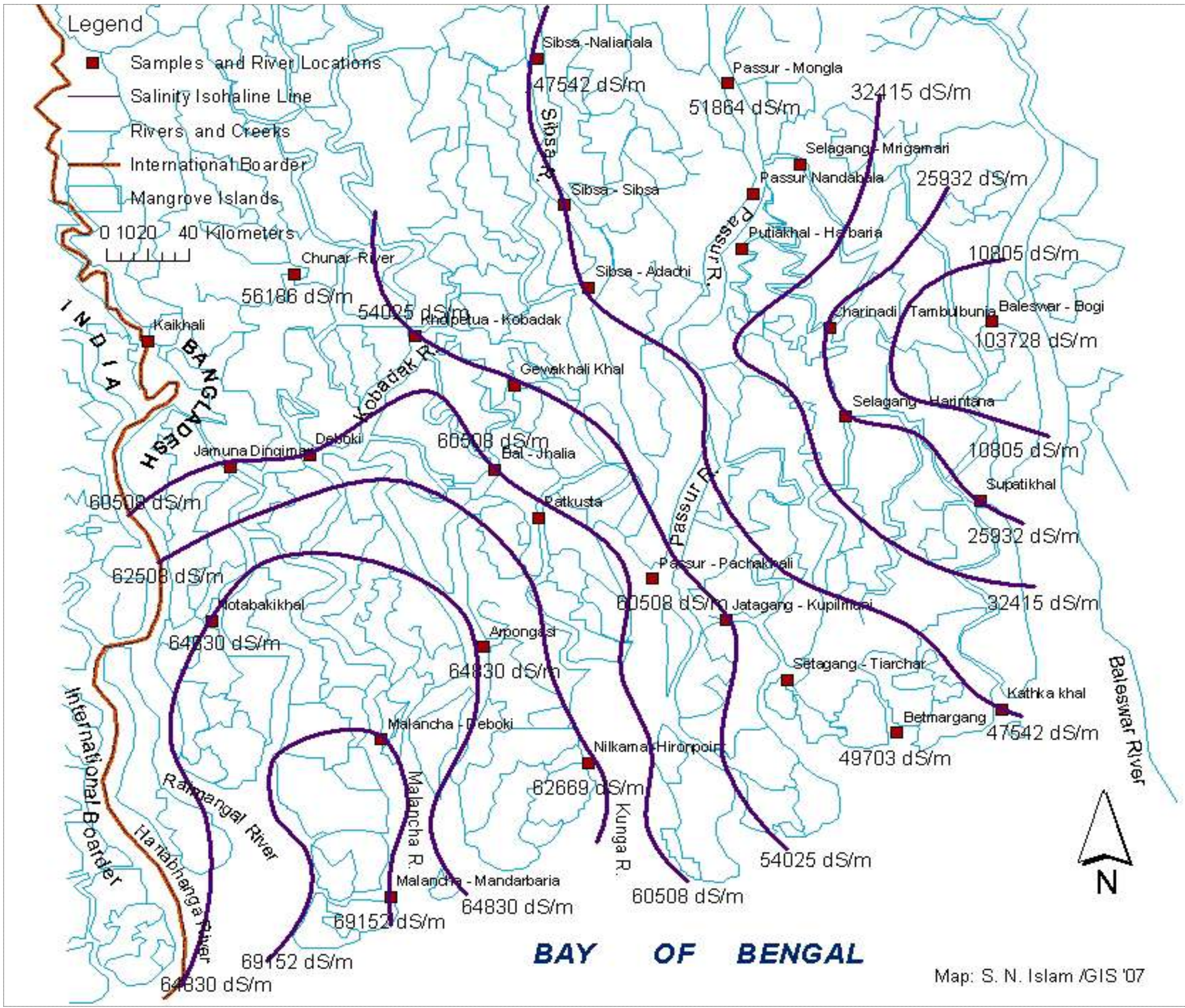


Figure 4.20 Water salinity Iso-haline and average highest values in 3 ecological zones

The Fourier polynomial models have ensured the yearly cycling salinity increasing behaviour. The cycling behaviour is good for understanding the trends for future threats. The figure (Figure 4.20) is showing the previous water salinity increasing trends which are called the salinity iso-haline, at the same time it has been ensured the present salinity trends and average peak values on the three ecological zones in the Sundarbans mangrove forest area. Models results are indicating that in the less saline zone the dry season peak salinity value is found

28352 dS/m (4 years average values) whereas before it was around 0 - 10805 dS/m, in the moderate saline zone where pervious values were found 10805 - 38898 dS/m (Figure 4.21) at present models showing the average value 49746 dS/m which is showing the marginal value to threshold line.

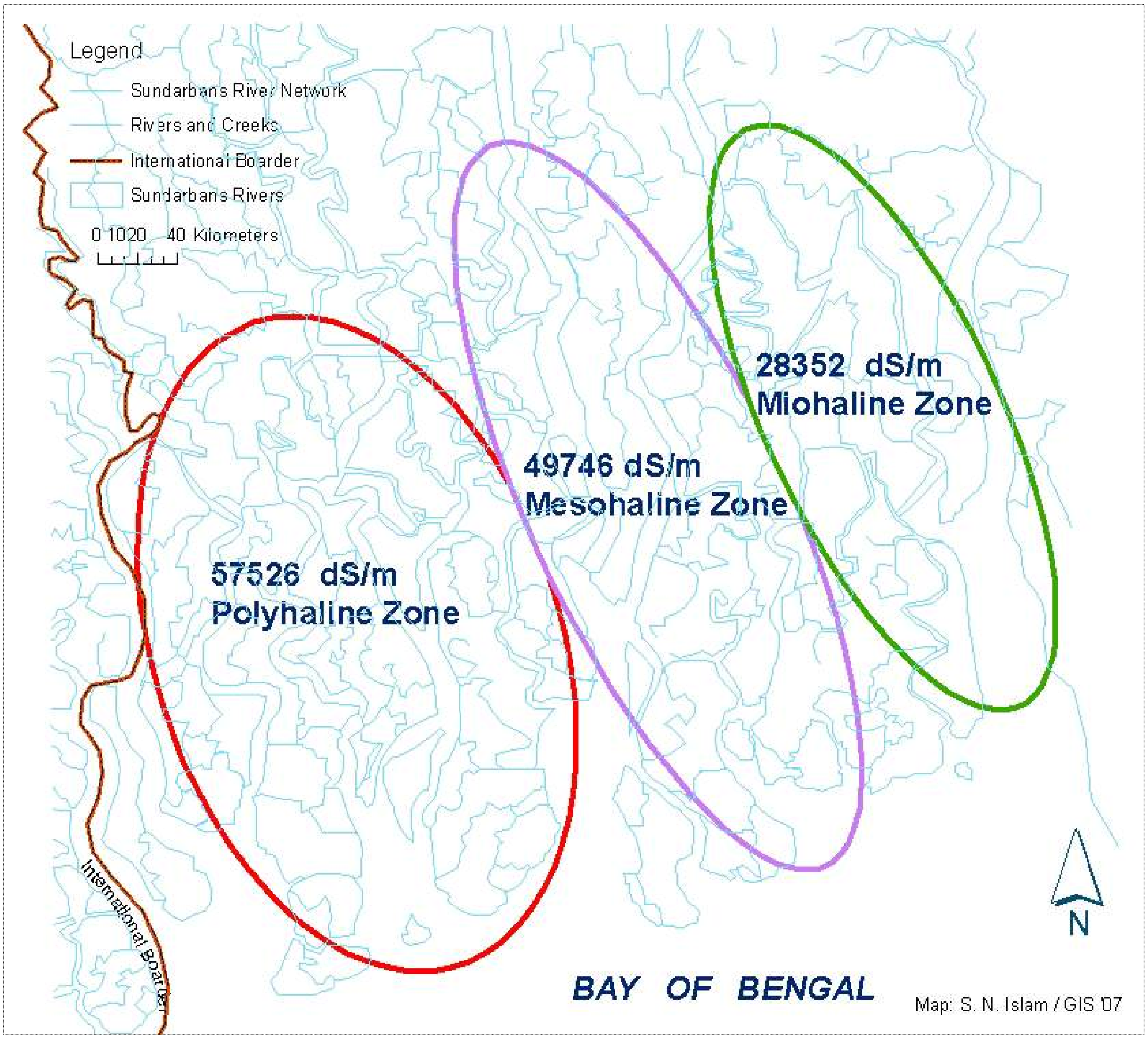


Figure 4.21 comparative salinity range in three ecological zones in the Sundarbans

The high salinity zone which is located in the south west part of Sundarbans and in the previous time the average highest salinity value was 38898-54025 dS/m whereas the present models are showing the increasing salinity values from 54025 dS/m - 69152 dS/m and the area of this zone has been extended in the north location. The present average peak salinity value is 57525.82 dS/m which has crossed the threshold value and there are 6 major influential rivers flowing through this ecological zone. The water salinity iso-haline map (Figure 4.20) of the Sundarbans mangrove wetlands which is little different from the (Figure 4.21) is showing the the recent average salinity trends in the whole region. According to three ecological zones the present situation is more harmful than before. Considering the highest salinity rate the eastern zone is still suitable for mangrove ecosystems; the middle area is rapidly turning to high salinity zone and the south western region is alarming situation which would be more harmful for some salinity sensitive mangroves plants and animals. On the other hand the high salinity trends are increasing from south to north and east to west. The north of the Sundarbans where settlements are presnt can be affected by high salinity. The agricultural cropping pattern is changing due to saline water and and soil salinity increase this trends would be penetrated in the north direction. The Fourier polynomial models are showing the cycling increasing trends of water salinity in the Sundarbans Rivers. Considering the result of all models and the threshold values of water salinity for Sundarbans case; it is clearly indicating and forcasting the message that for the upstream fresh water supply into the Sundarbans site is necessary for reducing the high salinity and protection of its mangrove wetlands ecosystems and cultural landscapes in the Sundarbans region.

Salinity thresholds value for crops and plants in the Sundarbans region

The salinity thresholds value is one kind of measurement scale of salinity for agricultural production and yield growth. On the other hand salinity thresholds value can measure the tolerance of salinity of particular crops in the certain region. In accordance with different climatic conditions, different type of crops carries different specific threshold values. Considering the mangroves production and yield growth Chaffey mentioned in (1985) that the maximum optimum value (Threshold value) of water salinity is 43220 dS/m (20 ppt) for mangrove growth and development, and Siddiqi mentioned in (1989) that the maximum seedling generation of mangroves species are in September when salinity rate is lower than 10805 dS/m. The study found more than 80 % area (4813.60 km^2) where salinity rate is 32415 dS/m which is the marginal situation in the Sundarbans region. There is a wide variation of vegetation in the Sundarbans. The freshwater zone and moderately front areas the mangrove forest and ecosystem consists of poor growth of plants species. On the other hand for different type of crops and plants and the yield production depends on the salinity increasing rate.

Table 4.4 In general vegetation types in respect of soil saline zones (after Ahmed, 1998 [`D` stands for dominant species])

Salinity zone (Salinity dS/m)	*Vegetation Types*
Miohaline Zone/ Oligohaline Zone Less saline zone Salinity < 10805 dS/m	*P. Karka, N. fruticans, E. agallocha, Pandanus foetidus, H. fomes (D), S.apetala, A. officinalis, C. ramiflora*
Mesohaline Zone Moderate saline zone Salinity 10805 - 32415 dS/m	*S. apetala, E. agallocha* (D), *S. caseolaris* *N. fruticans, A. officinalis, H. fomes* (D), *C. decandra* (D), *X. mekongensis*, *A. cucalata*, *P. paludosa* and *B. gymnorhiza* as undergrowth
Polyhaline Zone Highly saline zone Salinity 32415 - 69152 dS/m	*S.apetala* (D), *A. corniculatum* with *A. ilicifolius*, *A. offinalis, A. marina* (D) in sea front, *C. decandra* with degraded quality

The crops growth and production rates can be measured based on the soil salinity (NaCl) scale. It has projected the following options; a rough approximation of the yield decrease caused by salinity increasing trends; when

ECs < 4322 dS/m maximum optimum value, then there is no yield reduction

ECs > 8644 dS/m slight yield reduction when it will be 10 -15 % less

ECs > 12966 dS/m moderate reduction in growth and yield reduce 20 - 50 %

ECs > 21610 dS/m about 50 % yield reduction in susceptible cultivates.

The salinity threshold is the maximum average soil salinity (ECs) the crop can tolerate in rootzone without decline in yield. According to Ayers (1985) statement the salinity thresholds values of some specific crops would be a positive and motivation for the farmers in the Sundarbans region. There are two salinity thresholds which are considered in estimating the discharge requirements in the Gorai and Ganges Rivers. FAO (1976) recommended a 750 µS/cm salinity level for irrigation. However MPO (1987) accepted a level of 2000 µS/cm in the worst case scenario for agricultural crops cultivation. The farmer threshold is also permissible for human consumption. The Table 4.6 shows the thresholds limit of crops yield in the coastal and the Sundarbans region.

Table 4.5 Classification of coastal salinity (Source: Bangladesh Agricultural Research Council-BARC, 1990)

Salinity class	*EC dS/m*	*Plant growth condition*	*Rice yield reduction reported %*
Less saline (S_0)	< 2766	Salinity effects mostly negligible	None
Slight saline (S_1)	2766 - 5532	Yields of very sensitive crops may be restricted	1- 6
Moderately saline (S_2)	5532 - 8298	Yields of many crops are restricted	11 - 35
Saline (S_3)	8298 - 22129	Only salt tolerant crops yield satisfactorily	31 - 50
Highly saline (S_4)	> 22129	Only very salt tolerant crops yield satisfatorily	68 - 72

Table 4.6 The crops production and reduced rate based on soil salinity dS/m (after Ayers and Westcot, 1985).

Vegetable and Rawcrops	100% (dS/m)	90% (dS/m)	75% (dS/m)	50% (dS/m)	Salt Rating
Asparagus	3734.2	8436.5	15351.7	26830.9	T, VT
Broccoli	2627.8	3595.9	5117.2	7606.7	MS
Cabbage	1659.6	2627.8	4010.8	6361.9	M, MT
Carrot	968.1	1521.3	2627.8	4149.1	S
Cucumber	2351.1	3042.7	4010.8	5808.8	MS
Lettuce	1244.7	1936.2	2904.4	4702.3	MS
Onion	1106.4	1659.6	2489.5	4010.8	S
Pepper	1383.0	1659.6	3042.7	4702.3	MS
Potato	1521.3	2351.1	3457.6	5393.9	MS
Sweet Potato	1383.0	2212.9	3457.6	5532.1	MS
Tomato	2351.1	3180.9	4702.3	6915.2	MS
Rice (Paijum variety)	2766.0	5532.1	8298.2	27660.8	MS

(Note: S - Sensitive, MS - Moderately sensitive, MT - Moderately Tolerant, T - Tolarant, VT - Very tolerant).

Among many other crops all varities of rice paddy varities in Bangladesh are very sensitive to increases in salinity. The tolerance of rice paddy varities to salt concentration starts dropping sharply when the salinity exceeds 2000 μS/cm. Whenever the salinity concentration would be 16,000 μS/cm then plant growth drops to below 50% (MPO, 1986).

The above mentioned common crops are producing in the northern part of the Sundarbans region. The soil and water salinity has increased during the last three decades, as a result crops growth has decreased rapidly. The salinity threshold values for each particular crop is different therefore it is necessary to recognise the threshold values for the particular crops in the south western part of Bangladesh. Observing the real scenarios the farmers would be able to choose the specific crops which are suitable for that specific saline soil in the particular areas in the Sundarbans region. The salinity threshold values can be used as a potential indicator of crops production and mangrove species plantation in the area affecting by NaCl in the Sundarbans region.

Chapter 5
Proposals for the Sundarbans Ecosystems Development

5.1 Some specific proposals

The Sundarbans mangrove wetlands ecosystems and its protection strategies are now a key management concern in Bangladesh and the international communities. The mangrove wetlands and its wildlife preservation, flora and fauna conservation, protection of indigenous culture, cultural landscapes conservation, eco-tourism establishment, water quality control, and upstream Ganges water supply ensure the protection of mangrove wetlands ecosystems in the Sundarbans. These have become the most significant community issues. The Sundarbans mangrove wetlands have assumed economic importance, as people increasingly have interest in visiting and collecting the natural resources from these heritage sites. Protection and conservation of the mangrove ecosystem could contribute to environmental protection, reduction of environment degradation, and it could be a proper managed ecosystem and heritage preservation area for future generations.

- Wetlands ecosystems have historically and culturally been considered as on integral part of human habitation in Bangladesh. As a result, wetlands have frequently been altered or lost because their ecological functions and resulting values to society have not yet been understood, so it is the wise responsibility to protect these mangrove wetland ecosystems, by maintaining the upstream water supply in the Sundarbans region.
- The present management effort of the Sundarbans does not give proper attention to the destructive effects of development activities and tourism on such a highly sensitive ecosystem of the mangrove wetlands. It has been stated from the previous experiences that there were some constructional project activities such as coastal embankment, polders and dams. They had been constructed in the Sundarbans region which has created environmental and social negative impacts. Therefore to start any kind of developmental project activities, Social Vulnerability Assessment (SVA) and the Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA) should be under-taken as systematic approach of addressing the environmental issues and their consequences in

order to prove potential policies, plans, and programs in adequate management activities (Partidario et al., 2000) for sound ecosystems in the Sundarbans region.

- As it is difficult to segregate ecologically sensitive areas such as Sundarbans mangrove wetlands from the adjoining areas, environmental management and protective measures have to be undertaken within the framework of national planning.
- Sustainable national mangrove wetlands ecosystems management policy, which could be participatory management approach with special highlights on Sundarbans mangroves and its landscapes, should be at the ecosystems level.
- The Ganges water sharing between India and Bangladesh is just not a geo-techno-political issue, it is also a humanitarian problem, so the problem should be solved in a humanitarian way, and proper water sharing and supply to the down stream basin could be the appropriate solution for the protection of the Sundarbans mangrove wetlands ecosystems.
- Interaction is needed between Bangladesh and India concerning a common issue for appropriate use of Ganges water resources in the water catchment area. The coastal ecosystems balance and economic improvement is dependent on the Ganges water supply in the downstream. Therefore, the transboundary Ganges water sharing conflict should be considerably reduced, and an adequate coastal mangrove wetland ecosystems management plan should be developed and avoid the maximum ambiguities. To mitigate this water sharing conflict, the Indo-Bangladesh Joint River Commission (JRC) was set in 1972 that should work more actively and develop a scientific water flow monitoring system in the Ganges basin.
- The policy statements based on the core management plan of multiple uses of the mangrove wetlands resources, especially for forestry, fishery and shrimp farming, wildlife conservation and protection of biodiversity should be formulated on multidisciplinary approach. Where the local stakeholders participation and their benefits are classified.
- It should be ensured that an integrated approach to planning and management of Sundarbans mangroves and its cultural landscapes within the large scale of integrated coastal area management programme are implemented. There would be direct and indirect benefits like employment opportunity, resource based small business, eco-tourism, local

socio-economic improvement, women entrepreneurship, educational facilities and local development for the coastal community, stakeholders and international interest groups.

A clear distinction in conservation strategies also has to be made here.

i) The main aim of nature reserve should be the greatest or optimum attainable of biological productivity, diversity, and stability by restoring all ecological processes and their protection, regulation and carrier functions through scientific conservation management.

ii) In natural recreation parks, the aim should be to optimize recreational amenities in order to allow maximum recreational amenities and also allow maximum enjoyment with minimum damage to natural and cultural resources (Naveh, 1995).

- Top-dying of *Heritiera fomes* is associated with soils, which has high clay content and water salinity. For this reason, it is necessary to reduce the high rate of water and soil salinity in order to prevent top-dying and die-back diseases in the Sundarbans (Sobhan, 1973). On account of this conservation policies must be based on a proper appreciation of the social implications of the proposed studies.
- The marine hydro-engineering embankment construction approach for restoration of coastal wetlands should be undertaken as a concept to protect the tidal salinity intrusion and natural hazards mitigation in the Sundarbans areas.
- The wetland studies must be based on man environment research tradition, methodologies of proper conservation and management of mangrove wetlands have to take into consideration the local culture and social condition of individual cases, as well as people appreciation, attitude and perception of the wetland environment (Islam, 1995).

5. 2 Integrated sustainable management of mangrove ecosystems

The pressure on the coastal mangrove forest resources, their socio-economic, cultural value and its significance are increasing due to strong competition among the stakeholders and the communities utilising the mangrove resources. In such a critical situation some analytical findings suggest that an integrated and holistic approach to mangrove resource management is much more appropriate than other approaches (Salomons et al., 1999). The task of an integrated management approach is to work together and produce products services and gains or losses of socio-cultural significance from the available mangrove resources. The core objectives of the mangrove ecosystems management is the production of a socially and ecologically desirable resource utilisation and services that will balance mangrove wetlands ecosystems in the coastal area.

The future of the Sundarbans integrated mangrove management process should include:

- A holistic approach oriented integration of plans and programmes for local economic development and quality management of ecosystems. Appropriate capacity building, education and training are necessary to disseminate to the locals and stakeholders and such type of initiatives should start immediately.
- Global warming, sea level rise and vulnerability of coastal wetlands ecosystem is a new additional factor determining the long term management strategy for dealing with the mangrove wetland issue. A predicted sea level rise, accelerated by global warming will cause a further "squeezing" of the natural tidal land (Doodly, 2001). In the Sundarbans case, sea level rise would result in saline water moving further into the delta, which would be a catastrophe for mangrove and coastal wetland ecosystems in Bangladesh. The fate with different Sea Level Rise (SLR) and the impacts on the Sundarbans, this is if 1m SLR inundate 60% of the Sundarbans (Huq et al., 1999) and with 1.5 m SLR about 17 million (15%) of the population will have to be displaced, whereas 22,000 km² (16%) land will permanently be inundated, cyclone intensity will rise from 10 % to 25% as a result, reduction of mangroves areas will increase from 50-75 % (UNDP, 2000; Salar et al., 1994). In such situation climatic awareness education and applied training should be initiated in order to change the attitude of people and the government, and develop technically feasible devices to live with water related extremes. Some important issues should be considered such as a) Innovation partnership and networking for wetlands conservation, b) Cultural values of wetlands as engine for sustainable livelihood, c) Community-based management of coastal wetlands ecosystems, d) Restoration and motivation of stakeholder participation. Finally to strengthen the activity of preparedness systems, such as risk assessment and increase water storage and technology utilisation of the expected consequences of climate change situations. Beside these migration and adaptation are the two options that should be considered in minimizing the negative impacts.

- Appropriate integration of all elements of management, from planning and design, decision making, through implementation, maintenance, monitoring and evaluation within acceptable time frame, also needs to be addressed.
- Recognise the need to involve a broader community in policy debate in other to develop new innovative policies, management approaches and incentive mechanisms for institutional development and local water resource-base approaches (Dovers, 2005).
- Integration management approach of mangrove wetlands ecosystems in the Sundarbans is needed and it is essential for the protection of the whole coastal environment. For such an important task, responsibilities should be shared among the levels of Government, non-governmental organisations, local stakeholders, civil societies, national and international agencies and between public and private sectors those would like to safe these invaluable ecosystems for the future generation.
- Tourist facilities alter the natural landscapes, disturb natural areas and could become a source of pollution (Huybers et al., 2003). To realise such harmful environmental condition the modified 4 layers (Core Area, Eco-tourism zone, Buffer zone and Transitional Zone) eco-tourism model has been proposed for implementation as an appropriate tool, which is one of the alternative policies for local participation for the protection of disturbed landscapes, soil, water, biodiversity in the Sundarbans. Reduce substantial use of mangrove resources and establish eco-tourism by considering 350 meters buffer zone for tourists and the shrimp fry collectors in the reserve areas. Conservation and protection measures of eco-tourism should be included as a component of national wetlands development and management planning (Chaves, 2002; BPC, 2002; BPC, 2001). A multicultural approach to local agenda 21, in which eco-tourism is a component of sustainable development (Kay and Alder, 1999; Anderson, 2000).
- Taking into consideration the Bangladesh-Nepal (Ministry of Water Resources) joint investigation report on environmental impact assessment studies in 1989, where water supply problems was recognised and suggestion given to build water storages in the upstream of the Ganges, in order to mitigate and solve the water problems in the Ganges catchment area especially in Bangladesh water catchment area. The present studies finding also strongly suggest to build 7 water storages in Nepal with the multilateral agreement. Actually those 7 rivers of Nepal are carrying 71 % of fresh water annually at the Farakka

Barrage in the dry season. Therefore, those 7 water storages would be established in 3 different main river channel locations in the Ganges catchment at the Nepal portion, such as Pancheshar, Saptakoshi, Karnali, Kaligandhi 1, Kaligandhi 2, Seti and Trishul Ganga locations. It has been estimated that after construction of those proposed water storages in Nepal, Bangladesh can achieve extra 45,000 m³/sec water from upstream in the dry season. Figure 5.1 shows the proposed upstream water supply in the down stream through the Ganges and international navigation route through the Jamuna -Tistha basins.

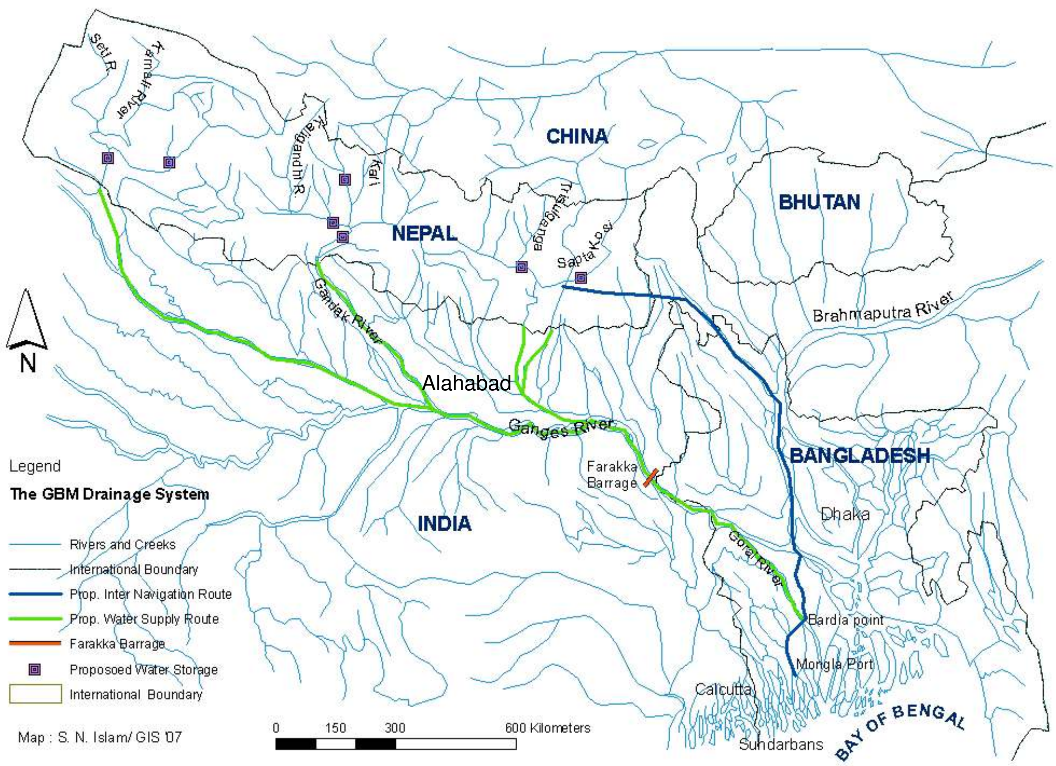


Figure 5.1 Proposed upstream water supply plan for Sundarbans and navigation route

To receive upstream water the Indian river basins are necessary for peaceful implementation of such project. This could solve the fresh water crisis between Bangladesh and India. In such case the green basin cooperation between India and Bangladesh is necessary for implementation of international navigation route connection from Saptakosi River basin (Nepal) to Tista River Basin (Bangladesh) and upstream water supply routes from reservoir sites (Nepal) to Farakka point in India and up to Bardia point in Bangladesh.

- The transboundary Ganges water sharing conflict and damage to ecosystems in the downstream of Bangladesh could be solved when ever minimum required upstream fresh water supply could be ensured in the Sundarbans region. Considering the present environmental degradation situation in the Sundarbans region, which has been estimated based on the Ganges water supply scenarios in figure 3.15 and figure 3.16, based on those two figures the present figure 5.2 shows the point (**A**) where water flows and salinity increase curve has been crossed. Figure 5.2 indicates that if the Ganges water level is at point **A** level, then there will be no problem for ecosystems, because the mangrove water salinity threshold value is 43220 dS/m (Clough, 1985). Therefore maintaining water salinity and balancing ecosystems at a minimum of 1200 m^3/sec Ganges water flows are essential at Harding bridge point. The Nepal Bangladesh water sharing approach could carry 45,000 m^3/sec flows in the dry season whereas for the protection of mangrove wetland ecosystems, the minimum requirement is 1200 m^3/sec flows at the Hardinge Bridge point in Bangladesh.

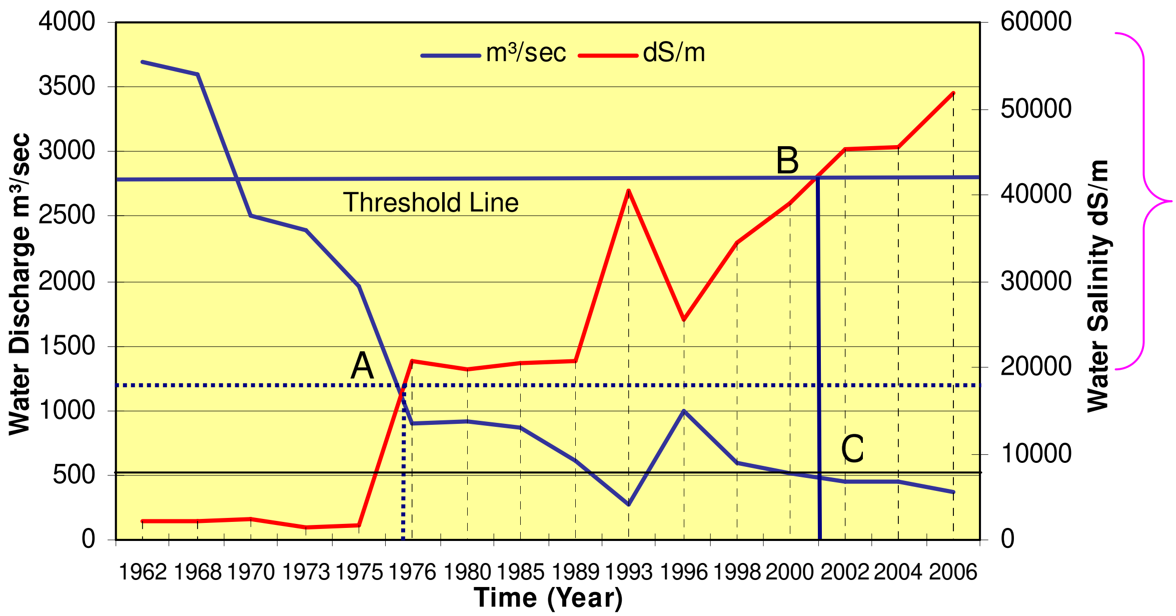


Figure 5.2 Considerable lines of water flows and salinity intrusion

If the Ganges River carries 1500 m^3/sec to 1200 m^3/sec water flows at the Hardinge Bridge point, then the maximum salinity in water could raise to 10500 dS/m, which would not be harmful for the mangrove wetland ecosystems in the Sundarbans. The water flow curve and salinity increase curve has crossed on the certain point (point **A**) in 1975. At this point the Ganges water flows was approximately 1200 m^3/sec and salinity rate was 18000 dS/m (figure 5.2). Line **A** shows the different salinity trends after and before the Farakka Barrage construction on the Ganges River in 1975, Point **B** shows the salinity intrusion line that crossed the water salinity threshold line. Therefore **B** is the highest considerable point of water salinity intrusion at Passur-Mongla River. After this point the salinity increasing trend would be harmful for ecosystems and dangerous for ecosystems services. This point (point **B**) can be introduced as maximum considerable point of salinity intrusion at the Passur-Mongla area. The Ganges water flow level **C** could be considered as the minimum level of water flows for the Mongla-Passur River point. Therefore, point **C** indicates the minimum quantity of water (500 m^3/sec). This quantity of fresh water is necessary and needed for the whole year to maintain the river basin, and mangrove ecosystems in the Sundarbans region. If 1200 m^3/sec fresh water is available at the Hardinge Bridge point then the water salinity will reduce and it will come back at the situation before the Farakka Barrage construction. Therefore, allowing 1500 m^3/sec fresh water to flow in the Hardinge Bridge at the Ganges basin could solve the ecosystems problem in the Sundarbans region.

The result of water salinity modelling on the Sundarbans rivers (Chapter 4), the alternative approach for fresh water supply (figure 5.1) and the current administrative management approach in the Sundarbans region could be used towards an integrated management plan for the Sundarbans mangrove wetland ecosystems and the cultural landscapes in the region. It could improved the standard and quality of lifestyle in local communities that depend on mangrove resources and on the other hand balancing biodiversity and the natural productivity of ecosystems in the Sundarbans mangrove wetlands (Gesamp, 1996; Davos, 1998).

Chapter 6
Conclusions

Cultural landscapes and wetlands have played a significant role in the development of human society. The rich natural wetland is an invaluable component of the environment, which supports a wide's array of biodiversity and the world's most productive ecosystems. The destruction of cultural landscapes and wetlands which are valuable resources has serious economic, ecological consequences for the community. The Sundarbans mangrove wetlands forests serve as a link between terrestrial and marine ecosystems. The ecosystems approach has been increasingly applied in water management, inland water resources, vegetation, wetlands, riverine floodplains, deltaic lands, wildlife habitats and human settlements. Mangrove vegetation stabilizes the coastline, enhances land building and enriches both soil and aquatic environments. The protection of mangrove wetlands forests and their sustainable use are not always priority issues almost all over the world. In recent years vast areas of mangrove wetlands have been destroyed due to scarcity of upstream fresh water and human intervention for developmental efforts. The lack of awareness, political, economic and technical choices of development, actually did not take part for long-term perspective. That is why it caused destruction for ecosystems with huge negative consequences for the water resources, which is directly connected to mangrove wetlands ecosystems.

A large part, almost 45 % of coastal mangrove wetlands have disappeared within the last three decades. After construction of the Farakka Barrage the water and soil salinity has increased and the limit of salinity threshold line has already been crossed. Salinity increase is caused for landscapes changes of the areas adjoining the Sundarbans; the surrounding land was popularly used for rice and agricultural crops which is now being used for shrimp farming. Therefore cultural landscapes are changing due to high salinity intrusion and shrimp farming. This trend is a serious threat for agricultural cropping and mangrove ecological balance of the Sundarbans and its cultural landscapes. Such degradation and shortage of fresh water flows and high salinity intrusion has brought about a biodiversity loss, degrading water quality, top-dying process, reduction of fish habitat, health risk for drinking water and threats for the whole ecosystems. During the last 100 years the Sundarbans has lost over 12 species while 21 species are on the red list of IUCN which is noticed the alarming situation in the Sundarbans.

The research on this particular issue and its findings must be considered to make an appropriate master plan for the protection and management of Sundarbans mangrove wetlands ecosystems in Bangladesh. The upstream fresh water supply to the Sundarbans is the central issue for adequate management of this hostile environmental. The Ganges water sharing and management is the most important and critical geo-political and environmental issues between Bangladesh and India. Water sharing is a long-term disputable issue, but until now constructive scientific water sharing, monitoring and management plan is still missing.

The actual goal of this research is a contribution makes a comprehensive management plan for the long-term conservation and protection of cultural landscapes and mangrove wetlands ecosystems in the Sundarbans region, where high salinity is one of the major problems for protection of mangrove wetlands ecosystems. Considering the present fragile environmental degradation the rivers water salinity modelling has been discussed extensively in Chapter 4, where the time series models with the Fourier polynomial approach has been analysed. The major 13 rivers carry fresh water from upstream by balancing the ecosystems in the coastal mangrove region. The 13 rivers have been represented from all corners and the three ecological zones of the Sundarbans. These rivers have been modelled and the results (Figure 4.5 to 4.17) show an increasing behaviour and most of these rivers have already crossed the water salinity threshold line. The Fourier polynomial models of 13 rivers in the Sundarbans are forecasting the future trends of salinity intrusion. The highest rate of water salinity is 58347 dS/m to 69152 dS/m, in such rate; all kinds of mangrove (flora fauna) species cannot tolerate or survive. Some mangrove species can survive within 86440 dS/m but the ratio of species is very small. Even in the Florida Bay mangroves are affected specially *Avicennia germinas* by die-back diseases and it is expected that they concide with periods of hypersalinity in Florida Bay (Carlson, 1995). In Australia there are serious die-back of mangroves around the Mackay Coast, the *Avicennia marina* is affected by toxic chemical. It appears to be taken up through the roots with salt molecules (Duke, 2004). In the Sundarbans case top-dying and dieback disease has found has found seriously in this study. Considering the high potentiality of mangrove biodiversity in the Sundarbans its protection is necessary and emergence. In such situation how could it be considered that the salinity increasing rate would not be harmful for all the mangrove species? On the other hand Sundarbans ecosystems are not only mangrove plants; it is the functions of biotic and abiotic systems. Considering the salinity intrusion and mangrove ecosystems it is necessary to make a separate specific research on every element of mangrove ecosystems, and the findings of such research will carry out a positive fundamental result for making an appropriate management plan for a long-term conservation of mangrove wetlands landscapes and its ecosystems.

This research finding will contribute to making an adequate management plan for the mangrove wetlands ecosystems in the Sundarbans region; the policy makers would be able to use this research finding as a guide line and as a reference. For the mangrove wetlands ecosystems and changes of cultural landscapes where the main fundamental issue is the Ganges water or surface water, therefore the Ganges transboundary water sharing between Bangladesh and India would be a priority issue for discussion and should ensure fresh water supply into the Sundarbans. Simultaneously other alternative approaches for the solution of this environmental problem have to be searched. The coastal region of Bangladesh especially the Sundarbans mangroves wetlands suffer from salinity problems caused of tidal flooding, direct inundation by saline water during the wet season (June-October) and a shortage of upstream fresh water. The intrusion of saline waters into the estuaries surface water systems, during the period of low river flows (February- May), lateral movement of saline groundwater main concern with the intrusion of saline water in the water systems. The following issues should be taken into consideration as a dynamic way to mitigate the water management and to share the conflict; and reduce the high salinity intrusion in the south western region in Bangladesh.

1. Internal rivers connection and transforming approach / River water supply through all connecting system plan. It can carry out a good result to make internal rivers connection and networking systems. In the meantime there are lot of rivers that have lost their connection, on account of this water cannot move or flow properly from north to south or east to west. This type of river netwoking system could be developed for the future environmental development in the Sundarbans region. In such case Jamuna River from the north (from the Gaibandha point) can be connected with Bangali - Atrai River and joint with Gorai through the Ganges on the certain state point where it is suitable considering hydrological and geomorphic point of view. Through this connection internal rivers water could flow from east-north to south west corner where Sundarbans is located.

2. Dredging the river beds and internal connection in the Sundarbans are needed. The water salinity model results show the different salinity behaviour in the Sundarbans. The higher rates are in the south and south western corner and low salinity rates are in the eastern and north eastern side of Sundarbans. So there could be an alternative solution if fresh water could flow in every corner inside of the Sundarbans, perhaps the increasing rate will be suddenly reduced whenever the upstream fresh water will enter the 13 rivers basins in the Sundarbans mangrove wetlands.
3. Considering the Geo-hydrological condition of the region the proposed possible dam in the upstream Ganges Barrage (Padma Barrage) should be constructed at the proper geographical location. There is a possibility to make such Barrage at the downstream of the Ganges as an alternative of Farakka Barrage. Where huge water can be reserved and could be used in the dry season by the south western part of Bangladesh through the Gorai river‘s channel. This would be a good idea and the Government of Bangladesh is already planning for it. But I do not agree with such sensitive project whether it would be a successful project or not. Reservoir making in Bangladesh, on a hydrological point of view would not be a wise idea, because all the rivers carry huge particles during the flooding times, only the Jamuna River carries 2.4 million tons particles and sediments in every year. A major portion of these particles and sediment load is deposited in linear channel and the river beds of the Sundarbans rivers. So the reservoir will be overloaded and filled out within a short time and then it will create another new environmental catastrophe in the deltaic coastal region.
4. Considering the natural influences on coastal mangrove wetlands, the Engineering hydrological dams would be constructed at the coastal off shore areas and river estuaries located in the south, where tidal inundation and cyclones are thrashing and damaging the mangrove resources and human settlements. Such type of coastal hydrological dams could trim down the destructive effects of wetlands ecosystems and human lives. It could be measured as a life belt for the coastal communities.
5. The Ganges is the Transboundary River between India and Bangladesh. There is a water sharing treaty between two countries. In reality the treaty is not working properly. For the greater interest of the Sundarbans world heritage site ecosystems and the benefits of stakeholders-water supply from Gages River should get priority. In the treaty the four key

important issues should be in place at the basin level i) Scope that mean legacy of users and uses whithin the basin, ii) Substantive norms relate to the competing uses economic, social and environmental issue should be reconciled, iii) Implementation instruments should specific and iv) Dispute settlement mechanisms.

6. The initiatives are needed to develop strategies for an adaptive adequate management plan based on monitoring of fresh water supply in the Ganges basin, flora, fauna and water quality with co-operation and appreciation of local people and international communities.
7. More in-depth applied research and training is needed especially on some potential issues as well as on hydrology, water quality and supply, soil salinity and fertility, vegetation, wildlife, precipitation and temperature, migration and settlement, climate change and coastal resource management, landscapes changing pattern, fisheries and marine resources etc. The local government authority, local research institutions, NGOs, civil societies and international research organisations can play a potential role to arrange such environmental awareness education, training and empirical research.
8. For effective use and research on transboundary surface water and wetlands resources; need to build-up data base knowledge, such detailed data on surface water, wetlands in Bangladesh are still lacking. Therefore an appropriate centre of research on wetland in the country should be developed and strengthened its capacities (Sharafuddin, 1992).
9. Governmental wills and political commitment is necessary for such transboundary issues within the transboundary catchments. The political inductility and good governance could arrange potential bilateral dialogues between India and Bangladesh. The initiatives from both Governmental sites could carry out satisfactory results for ending this pending game between the two countries and the Ganges water sharing issues.
10. Finally an interdisciplinary integrated management plan should be developed based on the water salinity model results which have been found in chapter 4.

The scarcity of the Ganges flows in the deltaic region is a challenge for cultural landscapes protection, biodiversity and mangrove wetland ecosystems management in the coastal region. The biota of the Sundarbans mangrove wetlands are highly influenced by salinity regimes of surface and groundwater systems and more significantly of water and soil. Saline water has large negative effects on the Sundarbans ecosystem and reduces crops growth and yields through increased soil and water salinity. At least 1.4 million ha of the coastal and offshore areas inhabited by about 15 % of the population are directly affected by salinity. The forest administration and inadequate management system is one of the main reason for the reserve forest destruction. Therefore to protect the mangrove wetlands ecosystems and endangered plants and animal species and their habitats high water salinity has to be reduced considering salinity thresholds values by increasing the Ganges fresh water input in the Sundarbans region. In such environmental degraded situation the discharge requirements indicate that it requires the highest discharge (in April) of 1500 m^3/sec at Hardinge bridge point on the Gages River to keep salinity below the threshold for the Sundarbans. The future development of ecosystems, the natural calamities and the approaches have been proposed in Figure 5.1 and 5.2 should be considered in making a master plan for the protection of mangrove wetland ecosystems. Therefore the community as a whole should realise this and may participate in the processes of conservation and improvement. The research on this particular issue and its findings must be considered to make a suitable master plan for Ganges water sharing and the management of the Sundarbans mangrove wetland ecosystems and its cultural landscapes in the Sundarbans region in Bangladesh.

References

Abbas, A. T. B. M. 1982. The Ganges water dispute. University Press Limited, Dhaka, Bangladesh.

Ahmed, A. U. 1998. Ecological security in a warmer world: The case of the Sundarbans. BUP monograph. Bangladesh Unnayan Parishad. Dhaka

Ahmed, A. U., and Reazuddin, M. 2000. Industrial pollution of water systems in Bangladesh, environmental system of surface water systems of Bangladesh. University Press Limited, Dhaka. Bangladesh.

Ahmed, F. 2001. Legal framework towards the conservation of the Sundarbans. Paper presented at the 1st national conference on the Sundarbans at University of Khulna, 14-16 February, Khulna. Bangladesh.

Ahmed, R. U., and Hivst, S. M. 1995. Wetland conservation and water resources development in Bangladesh. 14th Annual Meeting of the Society of wetland scientists, May 30- June 3, Edmonton Alberta, USA.

Ahsan, M., and Biswas, S.N. 2001. Soil and water salinity monitoring report, Khulna-Barisal Division, SRDI, Vol. 2. Dhaka, Bangladesh.

Alam, K. M. 2001. Integration of socio-economic and ecological data in conservation and management of floral diversity in the Sundarbans. In: Siddiqi, N. A. and Baksha, M.W. (eds.). Mangrove Research and Development, Proceedings of the National Workshop on Mangrove Research and Development at Bangladesh Forest Research Institute. Chittagong.

Ali, A. M. S., and Rahman, M. A. 1996. Shrimp cultivation and environmental destruction: case study on the Shatkhira region of Bangladesh (Bengali). In : Sultana, R. (ed.). Bhugul Patrika (Geographical Journal), Issue 14/ 1996. Department of Geography, Jahangirnagar University, Savar, Dhaka.

Alam, M., Nishat, A., and Siddiqi, S. N. 1998. Vulnerability of Bangladesh to climate change with special reference to inundation. In: Huq, S. Karim, Z. Asaduzzaman, M., and Mahtab, F. (eds.). In vulnerability and adaptation to climate change for Bangladesh. Kluwer Academic Publishers. Dordrecht, The Netherlands.

Alim, A. 1984. Soil and plant interaction in mangrove ecosystem. Paper presented in UNDP& UNESCO training seminar on geology. Sedimentology, erosion accretion in mangrove areas. Dhaka.

Amin, M. N., and Khan, N. A. 2001. A primer on the nature and management of resources of the Sundarbans. Grassroots voice: A journal of indigenous knowledge and development. Vol. IV. Issue 1. BARCIK, Dhaka.

Amarashinghe, M. D. 1988. Socio-economic status of human communities of selected mangrove areas on the west coast of Sri-Lanka. Mangrove ecosystems occasional papers. UNDP/UNESCO. Mangrove Project Asia and Pacific. No. 3

Anderson, D. L. 2000. The statistics of helium isotopes along the global spreading ridge system and the central limit theorem, geophysical research letters, 27, 16, 2401/2404.

Ansarul, K. 1995. Ecological implecation of changing natural flow of water on the Ganges river ecosystems. In: Hasan, J. M. (ed.). Women for water sharing. Academic Publishers. Dhaka. Bangladesh.

Anon, 1973. Reconnaissance soil survey report of sadar south and Cox's Bazar subdivision, Chittagong District. Department of Soil Survey. Dacca.

Anon, 1975. Soil taxonomy. A basic system of soil classification for making interpretative soil surveys. SCS-USDA handbook no. 436

Anon, 1987. Remote sensing monitoring component of mangrove afforestation project-I. Space Research and Remote Sensing Organisation (SPARRSO). Dhaka.

Anon, 1995. Integrated resource management plan of the Sundarbans reserved forest, Vol. 1. Draft final report of FAO/UNDP project BGD/84/056 – Integrated Resource Development of the Sundarbans Resource Forest, Khulna, Bangladesh.

Anon, 1998. Land degradation situation in Bangladesh. Soil division, BARC, Dhaka, Bangladesh.

Annette, M. P., and Donald, M. K. 2000. Managing global wetlands. In : Kent, D. M. (eds.). Applied wetlands science and technology. Lewis Publishers, New York. pp 377- 403

Ayers, R.S., and Westcott, W. 1985. Water quality for Agricultural organisation (FAO) of the United Nations. FAO irrigation drainage paper 29. Rome. Italy.

Bala, B. K. 1998. Energy and environment: Modelling and simulation, Nova science publishers, Inc. New York. USA.

BARC (Bangladesh Agricultural Research Council), 1990. Salinity of coastal soils. BARC, Dhaka. Bangladesh.

Bandyopadhyay, A. k. 1968. The Sundarbans mangrove forest experience on reclamation. Proceeding of workshop conservation mangrove areas to paddy cultivation. UNDP/ UNESCO, RAS/79/002, New Delhi. India.

Barbier, E. B. 1093. Sustainable use of wetlands valuing tropical wetland benefits: Economic methodologies and applications. The Geographical Journal. Vol. 159. No. 1

Begum, K. 1987. Tention over the Farakka Barrage – A techno political tangle in South Asia. University Press Limited, Dhaka, Bangladesh.

Begum, S. Barai, P. K., and Datta, D. K. 2001. Availability of forest biomass energy with reference to Bangladesh. Paper presented at the 1st national conference on the Sundarbans at University of Khulna, 14-16 February, Khulna.

Banerji, R. K. 1981. Cretaceous - eocene sedimentation, technism and biofacies in the Bengal Basin, Palaeogo. Palaeocli palaeoco. India.

Ben, C. Lindquist, A., and Wilson, D. 1995. Sharing the Ganges – The politics and technology of river development. University Press Limited. Dhaka.

Bhattacharya, D., and Chowdhury, M. 1985. Education based on prehistory in conserving biodiversity. University of California and Rodlands University USA. A paper presented at the national conference.

Bird, E. C. F. 1967. An introduction to systematic geomorphology; Coasts. Massachusetts Institute of Technology, MIT Press, Massachusetts. USA.

Birks, H. H. Birks, H. J. B. Emil., Kaland, P. E., and Moe, D. (eds.). 1999. The cultural landscape past, present and future. Cambridge University Press. Cambridge. UK.

Biswas, A., and Hitto, J. (eds.). 2001. Sustainable development of the Ganges – Bramaputra-Meghna basin, United Nations University Press, Tokyo, Japan.

Biswas, A., and Utto, J. I. (eds.). 2000. Water for urban areas of the developing world in the twenty first century: Water resource management and policy- Water for urban areas and challenges and perspective. UNU, Tokyo. pp1-23

Blasco, F. 1975. The mangroves of India. Institut Francis de Pondichery, Travaux de las section scientifique et technique, tome XIV, Facicule 1, Pondichery, India.

Blower, J. H. 1985. Sundarbans forest inventory project, Bangladesh: wildlife conservation in the Sundarbans, ODA project report 151, Land resource development centre, Surbiton, Survey. UK

Bose, S. K., and Bhattacharjee, D. K. 2001. Utilisation aspects of mangrove species. In: Siddiqi, N. A., and Baksha, M. W. (eds.). Mangrove research and development - proceedings of the national workshop on mangrove research and development at BFRI, Chittagong. 15-16 May. pp108-113

Boyce, M. S., and Haney, A. (eds.). 1997. Ecosystem management. Applications for sustainable forest and wildlife resources. Yale University Press. New Haven and London.

Bowman, H. H. M. 1917. Ecology and Physiology of the red mangrove. Proceedings. American Philosophical Science. 56: pp 589-672.

BPC-(Bangladesh Parjatan Corporation) 2001. Ecotourism implementation in the Sundarbans and recommendation for development. Report prepared by recommendation making committee and BPC. No. P- 1(56)/87 (part-1)/336. Dhaka. Bangladesh

Brammer, H. 1999. Agricultural disaster management in Bangladesh- Salinisation. University Press Limited, Dhaka, Bangladesh. pp 331-336

Brouwer, R. Langford, I. H. Bateman, I. J., and Turner, R. K. 2001. A meta-analysis of wetland contingent valuation studies. In: Turner, B., and Ader, (eds.). Economic of coastal and water resources: valuing environmental Functions, Kluwer Academic Publishers, and The Netherlands. pp 305-322

Brown, B. E. 1997. Integrated coastal management in South Asia. Department for International Development. University of Newcastle. UK.

Buhmann and Ervin (eds.). 2003. Trends in landscape modeling. Proceeding at Anhalt University of Applied Sciences 2003. Wichmann Verlag, Heidelberg.

Carley, M., and Christie, I. 1993. Managing sustainable development. Minneapolis. University of Minnesota Press. USA.

Chaffey, D. R. Miller, F. R., and Sandom, J. H. 1985. A forest inventory of the Sundarbans, Bangladesh; Main report. Project report No. 140, Ovearseas Development Administration, London, UK.

Champion, H. G., and Khattak, G. M. 1965. Mannual of silviculture for Pakistan. Pakistan Forest Institute. Peshawar, Pakistan.

Chan, H. T. 1996. Mangrove reforestation in peninsular Malaysia: A Case study of matang. In: Field, C. D. (ed.). Restoration of mangrove ecosystems. ISME. Okinawa. Japan

Chan, H. T. Ong, J. E., Gong, W. K., and Sasekumar, A. 1993. The socio-economic, ecological and environmental values of mangrove ecosystems in Malaysia and their present state of conservation. In: Clough, B. F. (ed.). The economic and environmental values of mangrove forests and their present state of conservation in the south-east Asia/Pacific region. ITTO/ISME/JIAM, Japan.

Chapman, V. J. 1975. Mangrove biogeography. In: Walsh, G., Snedaker, S. and Teas, H. (eds.). Proceedings of the International symposium on biology and management on mangroves, 8-11 October, 1974, Honolulu. pp 3-22

Chapman, V. J. 1976. The salinity problem in general, its importance, and distribution with special reference to natural halophytes. In: Poljakoff M. A., and Gale, J (eds.). Plants in saline environments. Springer Verlag Berlin. pp 7-23

Chaves, L. G. 2002. Tourism, recreation and eco-tourism management plan for the Sundarbans reserve forest. An integrated management approach to ecotourism development. Sundarbans Biodiversity Conservation Project Bangladesh. ADB: 1643 BAN (ARCADIS Euroconsult project no. 417.44631)

Christensen, B. 1984. Ecological aspects of the Sundarbans. FO: TCP/BGD/2309 (Mf). FAO, Rome. Italy.

Choudhury, A. M. Quadir, D. A., and Islam, J. 1990. Study of Chokaria Sundarbans using remote sensing techniques. SPARRSO. Dhaka.

Choudhury, K. Waliuzzaman, M., and Nishat, A. 2001. The Bangladesh Sundarbans A Photoreal Sojourn. IUCN - the World Conservation Union, Bangladesh country office, Dhaka. pp VI, 145

Chowdhury, F. Ali, M. A., and Rahman, A. 2001. People's report on Bangladesh environment 2001 - In search of a people's perspective on environment in Bangladesh. Dhaka.

Chowdhury, A. M. 1968. Working plan of the Sundarbans forest division for the period 1960 - 61 to 1979 - 80. East Pakistan Government Press. Dhaka.

Choudhury, A. M. 1984. Integrated development of the Sundarbans, Bangladesh: Silvicultural aspects of the Sundarbans FAO report No/ TCP /BGD/ 23 09 MO, W/ R003.

Choudhury, A., and Chaudhury, A. B. 1994. Mangroves of the Sundarbans, Volume one: India. IUCN-The World Conservation Union, Bangkok, Thailand.

Chowdhury, S. H. 1995. Draft report on Entomology of the sundarbans reserve forest. FAO/UNDP project. BGD/84/ 056. Integrated resource development of the Sundarbans Reserve Forest. Khulna.

Coleman, J. M. 1964. Bramahputra River: channel process and sedimentation. Sediment Geology. 3 (2/3). pp 129-239

Colugh, B. F. 1985. Factors regulating mangrove ecosystem primary productivity. Proceedings of the UNDP/ UNESCO regional project RAS/79/ 002 workshops on mangrove ecosystem dynamics, Papua New Guinea. pp 79-85

Curtis, S. J. 1933. Working plan for the forest of the Sundarbans division for the period from April 1, 1931 to March 31, 1951. Vol.1, Bengal Government Press, Calcutta, India.

Curry, J. M., and Mcguire, S. 2002. Community on land / Community, ecology, and the public interest. Rowman & Littlefield Publishers, Maryland. USA. pp141-175

Das, S. 1980. Mangrove forest of Bangladesh (Management, exploitation and economics) Paper presented at the 4th and 5th Annual Bangladesh Science Conference at Rajshahi University. Rajshahi. Bangladesh.

Das, S. C. 1989. Coastal marine pollution in Bangladesh. paper presented at the 5th Conference of the Bangladesh National Geographical Association, 2-5 March at Rajshahi. Bangladesh.

Das, S. C. 1992. Physical oceanography of the Bay of Bengal. In: Elahi, K. M., Sharif, A. H. M. R., and Kalam, A. K. M. A. (eds.). Bangladesh: Geography, Environment and Development, Bangladesh National Geographical Association. Dhaka. pp 36-52

Davos, C. A. 1998. Sustaining co-operation for coastal sustainbility, Journal of environmental management, 52. USA. pp 379-387

Dewan, A. M., and Nizamuddin, K. 1998. A Geographical analysis of salinity in the South-western region of Bangladesh in Bhugal Patrika (Bengali), vol. 17, 1998, Dhaka.

Dickinson, G., and Murphy, K. 1998. Ecosystems routledge introductions to environments series. Routledge, London, UK.

Dovers, S. 2005. Policy analysis, Environment and sustainability. In: Grafton, R. Q. Robin, L., and Wasson, R. J. (eds.). Understanding the Environment

Doody, J. P. 2000. Coastal conservation and management – an ecological perspective. Kluwer Academic Publishers, London. UK.

Drengson, A., and Taylor, D. (eds.). 1997. Ecoforestry – The art and sciences of sustainable forest use. New society publishers. BC, Canada.

Droste, B. V. Plachter, H., and Rössler, M. 1995. Cultural landscapes of universal value Gustav Fischer-Verlag Jena, Stuttgart, Germany.

Dugan, P., and Bellemy, D. 1993. Wetlands in danger - A world conservation Atlas. Oxford University Press. New York.

Duke, N. C. 1995. Genetic diversity, distributional barriers and raffing continents /more thoughts on the evolution of mangroves - Hydrobiologia 295: 167/181. Australia

Duke, N. C., Bell, A. M., Pederson, D. K., Roelfsema, C. M, Godson, L. M., Zahmel, K. N. Mackenzie, J., and Bengston-Nash, S. 2004. Mackey mangrove dieback investigations in 2002 with recommendations for further research, monitoring and management, Centre for Marine Studies, UQ. Australia.

Dykyjova, D., and Ulehlova, B. 1998. The Production ecology of wetlands. In: Wetlake, D. F. Kvet, J., and Szczepanski, A. (eds.). Mineral economy and cycling of minerals in wetlands.

EGIS - (Environmental and Geographical Information Studies), 2000. Bangladesh Water Development Board - Environmental baseline of Gorai river restoration project. (EGIS – I, EGIS – II, and EGIS – III). Environment and GIS support project for water sector planning, Ministry of Water Resources, Government of the Peoples Bangladesh. Dhaka.

ESCAP-(Economic and Social Co-operation for Asia and the Pacific), 1988. Coastal environmental management plan for Bangladesh. Vol. 2. Final: report. ESCAP, Bangkok, Thailand.

ESCAP-(Economic and Social Co-operation for Asia and the Pacific), 1999. Economic and social commission for Asia and the Pacific - guidelines on integrated planning for sustainable tourism development. United Nations, New York.USA.

Elahi, K. M. Das, S. C., and Sultana, S. 1998. Geography of coastal environment: A study of selected issues. In: Bayes, A., and Mahammad, A. (eds.). Bangladesh at 25, An analytical discourse on development. The university press limited, Dhaka, Bangladesh. pp 336-368

Erickson, P. A. 1994. A practical guide to environmental impact assessment. Academic Press, London. UK.

FAO, 1976. Water quality for agriculture, FAO irrigation project, Vol.3. Morphological studies. Sir William Halcrow and Partners Ltd. Dhaka.

FAO, 1994. Mangrove management guidelines. FAO, Rome, Italy.

FAO / UNDP.1995. Project BGD/ 84/056- Integrated resource development of the Sundarbans reserved forest. Report on mangrove silviculture, vol.1, by karim, A. Khulna. pp 16-19

FAP 4, 1993. South west area water resources management project, Vol.3. Morphological studies. Sir William Halcrow and Partners Ltd.

Fairbrother, N. 1974. The Nature of landscapes. Eelco Hoofman, Edinburg. UK

Farina, A. 1998. Principles and methods in landscape ecology. London: Chapman & Hall.

Farzana, N., and Nadia, M. 2001. Water disputes in South Asia. www.issi.org.pk/strategic_studies_htm/2001

Faizuddin, M. Rahman, M. M. Shahidullah, M. Siddiq, H. U. A. Hasnin, M., and Rashid, M. H. 1999. Plantation of golpata (*Nypa fruticans*) in the newly accreted sites of the Sundarbans mangrove forest of Bangladesh.

Forestal, 1960. Forestry inventory 1958-59 Sundarbans forest. Forestal International Incorporated Canada.

Folke, C. 1998. Ecosystem approaches to the management and allocation of critical resources. In: Pace, M. L., and Groffman, P. M. (eds.). Successes, limitation, and frontiers in ecosystem science. Springer New York. pp 313 -338

Gesamp, 1996. The contributions of science to integrated coastal management. Report 61, FAO, Rome. Italy.

Gleick, P. 1998. The world's water. Island Press, Washington DC. USA

Gibson, I. A. S. 1975. Report on a Visit to the People's Republic of Bangladesh, 28 February to 1st April and 13 to 17 April, (unpublished report) Overseas Development Administration, London.

Gnauck, A. 2006. Funktoren und signale- zur signalanalyse ökologischer prozesse. In: Gnauck, A. (Hrsg.): Modellierung und simulation von ökosystemen. Workshop Kölpinsee 2004. Shaker Verlag, Aachen, Germany. pp 192-224

Gonzalo, C. 1998. Biodiversity conservation in the Sundarbans reserve forest. World Bank technical report on 16th January, Dhaka.

Gupta, H. P. 1981. Palaeonvironments during Holocene time in Bengal Basin, India as reflected by Palynology. Palaeobotanist, 27(2), 138-159.

Huq, S. Haider, R., and Rahman, A. A. (eds.). 1991. Cyclone '1991 - An environmental and perceptional study. Bangladesh centre for advanced studies (BCAS), Dhaka, Bangladesh.

Haque, M. I. 1996. Water Policy formulation and implementation in Bangladesh (eds.) by Howsam, P., and Carter, R. 1996 – Water Policy: Allocation management in practice. E and FN SPON. London. UK. pp 13-20.

Hoque, M. M., and Alam, S. M. K. 1995. Post Farakka dry season surface and ground water conditions in the Ganges and vicinity. In: Hasna, J. M. (ed.). Women for water sharing. Academic Publishers. Dhaka.

Hartung, F. Wevner, R, M. I. Alam, S. K. S. Khan, S. Paul, A. R., and Mahlback, H. P. 1998. Association of phytopathogenic bacteria with top dying disease of Sundri tree (*Heritiera fomes*) in Bangladesh. Angewandte Botanik. pp 48-72

Hasan, M. Rahman, M. S., and Haider, M. Z. 2001. Some facts and observations related to salinity and the river systems of the Sundarbans mangroves forest. Paper presented at the 1st national conference at University of Khulna, 14-16 February, Khulna. Bangladesh.

Hasna, J. M. (ed.). 1995. Women for Water Sharing. Academic Publishers. Dhaka.

Hasna, J. M. Rashid, H., and Rahman, A. A. (eds.). 1998. Bangladesh coastal area resource development and management. Executive summery and recommendations of the national workshop report I. CADMA, Dhaka.

Hassan, M. M. 2001. Water and soil quality of Sundarbans. Paper presented at 1st national conference on the Sundarbans at University of Khulna, 14-16 February, Khulna.

Hawley, A. H. 1986. Human ecology – a theoretical essay. The University of Chicago Press. Chicago. USA

Head, L. (ed.). 2000. Cultural landscapes and environmental Change. ARNOLD. Oxford University Press Inc. New York.

Heining, R. L. 1892. Working plan of the Sundarbans Government forest, Khulna and 24 – Pargana Districts, Bengal, and Calcutta. Bengal Secretariat Press. India.

Helalsiddiqi, A. S. M. 1999. Minor forest products in the Sundarbans of Bangladesh. Journal of non-timber forest products. 6 (1 and 2). Dhaka

Holmgren, S. 1994. An environmental Assessment of the Bay of Bengal region. BOBP / REP / 67. SWEDMAR/ BOBP

Hossain, T. M. Paul. Z. H. Khan, A. T. M. Alam, M. L. Islam, and Azad, A. K. M. 2001. Salinity trends in the Sundarbans and its vegetation. In: Siddiqi, N. A., and Baksha, M. W. (eds.) Mangrove research and development. Proceeding of national workshop. 15-16 May, Chittagong. Bangladesh.

Hutchings, P., and Saenger, P. 1987. Ecology of mangroves. University of Queensland Press. Queensland, Australia.

Huq, S. Karim, Z. Asaduzzaman, M., and Mahtab, F. (eds.). 1999. Vulnerability and adaptation to climate change for Bangladesh. Kluwer Academic Publishers, London.

Hussain, Z., and Acharya, G. (eds.). 1994. Mangroves of the Sundarbans, Volume Two: Bangladesh. IUCN – The World Conservation Union. Dyna Print, Bangkok, Thailand.

Huybers, T. Bennett, J., and Elgar, E. (eds.). 2003. Environmental management and the competitiveness of nature-Based tourism destinations. Edward Elgar Publishing. UK.

Iftekhar, S. M., and Islam, R. M. 2002. Vegetation dynamics in the Sundarbans and its implication on the integrated coastal zone management of Bangladesh. Dhaka

Ingegnoli, V. 2002. Landscape ecology: a widening foundation. Springer-Verlag Berlin.

Islam, M. A. 1995. Environment land use and natural hazards in Bangladesh. Dhaka University. Dhanshish Mudrayan, New market area. Dhaka.

Islam, M. S. 2001. Sea-level changes in Bangladesh: the last ten thousand years. Asiatic Society of Bangladesh, Asiatic Civil Military Press, Dhaka.

Islam, S. N. 2002. Sustainable Eco-tourism as a practicable site management policy? A case study on the Sundarbans natural world heritage site in Bangladesh. Master's Thesis at the International study course- World Heritage Studies, Brandenburg University of Technology at Cottbus, Germany.

Islam, S. N. 2003. Sustainable Eco-tourism as a practical site management policy. AHDPH, Dhaka, Bangladesh.

Islam, S. N. 2005a. Cultural landscapes changing and threats to ecosystems: A case study on the Sundarbans for a management plan. In: Gnauck, A. (ed.). Modelling and Simulation on Ecosystems. Shaker- Verlag, Aachen. Germany. pp 190-2004

Islam, S. N. Engelberth, S. E., and Rina, A. S. 2005b. Cultural Integrity as a Criterion of SEA. In: Schmidt, M., Elsa, J., and Albrecht, E. (eds.) Implementing strategic environmental Assessment. Springer –Verlag, Heidelberg, Germany. pp 409 - 420.

IUCN, 1992. People, development and environment complex interlinkages in Bangladesh. Proceedings of a national symposium held in 3-4 November. Dhaka. Bangladesh.

IWM- (Institute of Water Management), 2003. Sundarbans Biodiversity Conservation Project - Surface water modelling TA No. 3158-BAN. Final report. Volume 1. IWM, Dhaka. Bangladesh.

Jabber, M. A. 1992. A draft report on special study on pattern of erosion and accretion of land in the coastal belt of Bangladesh using satellite imagery and Aerial photographs. APARRSO, Dhaka.

Jabbar, M. A. 1995. Farakka Barrage and its impact on the environment of Southwest region of Bangladesh. In: Hasna, J. M. (ed.). Women for water sharing. Academic Publisher. Dhaka, Bangladesh.

Jenderedjian, K. K. 2004. Arax wetland and perspectives of transboundary conservation in south Caucasus region – contribution to the conference on integrated water management of transboundary catchment: a contribution from transact. Venice. Italy

Jörgensen, S. E., and Muller, F. (eds.). 2000. Handbook of ecosystem theories and management. Lewis publishers, Washington D.C.

Joseph, P. S. 2006. The environmental management doe better supply of fresh in transboundary river: The Ganges could run dry. In: Perez, J. G. (ed.). Proceedings of III international symposium on Transboundary Waters Management- Overcoming water management boundaries. Universidad de Castilla-La Mancha. 30 May-2 June, Ciudad Real, Spain.

Katebi, M. N. A. 2001. Sundarbans and Forestry. In: Haider (ed.). Cyclone ’91 – an environmental and perceptional study. BCAS. Dhaka. pp 79-100

Karim, A. 1988. Environmental factors and distributions of Mangroves in Sundarbans with special reference to *Heritiera fomes* Buch.Ham. PhD thesis at University of Calcutta. India.

Karim, A. 1995. Mangrove cilviculture, vol. 1. Draft report of FAO/ UNDP project BGD/84/056-integrated resource development of the Sundarbans reserve forest, Khulna.

Kay, R., and Alder, J. 1999. Coastal planning and management. E & FN SPON – An Imprint of Routledge, London.

Khan, M. A. R. 1986. Wildlife of Bangladesh mangrove ecosystems. Journal of Bombay natural historical sciences. Bombay. India.

Khan, M. S., and Shafi, M. 1992. Use of Korea trees with branches, tops, bark and Keora thinning for hardboard manufacture. Brangladesh Journal of Forest Science. Chittagong

Khan, A. A. 1993. Freshwater wetlands in Bangladesh: Opportunities and options. In: Nishat, A. Hussain, Z. Roy, M. K., and Karim, A. (eds.) Freshwater wetlands in Bangladesh – Issues and approaches for Management. IUCN, Dhaka.

Khan, A. H. 1995. Ganges Water Sharing: An overview. In: Hasna, J. M. (ed.). Women for Water Sharing. Academic Publishers. Dhaka. pp 1-33

Khan, M. S. Haq, E. Huq, S. Rahman, A. A. Rashid, S. M. A., and Ahmed, H. (eds.). 1994. Wetlands of Bangladesh. BCAS, Dhaka. Bangladesh.

Lacerda, L. D. D. (ed.). 2001. Mangrove ecosystems, function and management. Springer-Verlag Berlin, Germany.

MAB-(Man and Biosphere) UNESCO, 1975. Ecological effects of human activities on the value and resources of lakes. Marshes, rivers, Deltas and coastal zones. UNESCO-Paris.

Mafizuddin, M., and Ali, M. M. 1993. Alluvial characteristics of the changes floodplain. In: Arephin, S. (ed.). The Journal of the Bangladesh National Geographical Association (BNGA). Vol. 19 Nos 1 and 2, 1991, Department of Geography, Jahangirnagar University, Savar, Dhaka. pp 1-12

Meining, D. 1979. Interpretations of the ordinary landscape. N.Y: Oxford University Press. USA

Mepham, R. H. 1983. Mangrove floras of the Southern continents South Africa. Journal of Botany. pp 2: 1-8.

MPO - (Master Plan Organisation), 1986. Coastal shrimp aquaculture resources, Technical paper 18. BWDB/MPO, Dhaka

MPO - (Master Plan Organisation), 1987. Surface water availability. Technical report No. 10. MPO, Dhaka.

MAP, 2000. Technical report - fisheries and flood control drainage and irrigation development. Dhaka, Bangladesh

Murtuza, G. 2001. Socio-economic condition of the people living around the Sundarbans forest area and their opinions on forest resources conservation- a study on Koyra Upazila, Khulna Zila. Paper presented at the 1st national conference on the Sundarbans at University of Khulna, 14-16 February, Khulna.

Muniruzzaman, M. 2003. Hydro-politics of the Farakka Barrage. www.sdnpbd.org/river-basin/bangla

Mitsch, W. J., and Gosselink, J. G. 2000. Wetlands 3rd Edition. John Wiley & Sons, Inc. New York. USA. p 1-106, 335-373

Milliman, J. D. Broadus, J. M., and Gable, F. 1989. Environmental and economic implecation of rising sea level and subsiding deltas. The Nile and Bengal examples. Ambio. 18(6). pp-340-365

Mirza, M. Q. M. 1998. Diversion of the Ganges water at Farakka and its effects on salinity in Bangladesh. Environmental management Vol. 22. No.5. Springer–Verlag. New York. pp 711-722.

MoEF-(Ministry of Environment and Forest), 1994. Vulnerability of Bangladesh to climate change and sea level rise. Summary Report- 1994. Concepts and tools for calculating risk in integrated coastal zone management. Government of the People's Republic of Bangladesh, Dhaka.

MoFL- (Ministry of Fisheries and Livestock), 2002. Balancing resource conservation with livelihood protection for shrimp fry collections: an integrated approach to managing coastal resources. Department of Fisheries and Livestock, Dhaka, Bangladesh. pp 1-14

MoFL-(Ministry of Fisheries and Livestock), 2002. Shrimp aquaculture in Bangladesh - A vision for the future, Department of Fisheries Ministry of Fisheries and Livestock. October 2002. Dhaka, Bangladesh. pp 1-7

MoWR-(Ministry of Water Resources), 2000. Land use conflicts arising from shrimp and prawn cultivation Shrimp culture costs and returns National Water Management Plan Project, Water Resource Planning Organisation, Government of the Peoples Republic of Bangladesh, Draft development strategy volume no. 8. Annex J. Economics. Helcrow Mott Macdonald Consultants.

Mondal, M. K. 1992. An Approach to increase land productivity in the coastal region. Proceedings of the workshop on coastal zone management in Bangladesh. National commission for UNESCO. Dhaka.

Morley, R. J. 2000. Origin and evolution of tropical rain forests. John Willy & Sons Ltd. New York, USA. pp 1- 43.

Naveh, Z. 1995. Conservation, restoration and research priorities for Mediterranean uplands threatened by global climate change (eds.). Moreno and Oechel – Global change and Mediterranean type ecosystems. Springer-Verlag Berlin.

Nishat, A. 1993. Freshwater wetlands in Bangladesh: Status and Issues. In: Nishat, A. Hussain, Z. Roy, M. K., and Karim, A. (eds.). Freshwater wetlands in Bangladesh- issues and approaches for management. IUCN. pp 1-22.

Nishat, A. 2006. Water at Farakka Barrage in 2006. www.ajkekagoj.com/2006/April 08/

Novak, J. D. 2001. Assessing understanding in biology. Journal of biological education 35 (3).

ODA - (Overseas Development Authority), 1985. A forest preventory of the Sundarbans, Bangladesh. (Main report). Overseas Development Administration. England.

Parikh, J., and Datye, H. (eds.). 2003. Sustainable management of wetlands biodiversity and beyond. Sage publishers. New Delhi, India.

Partidario, M. R., and Clark, R. (eds.). 2000. Perspectives on strategic environmental assessment Lewis Publishers. New York. pp 2-16

Perry, J., and Vanderklein, E. 1992. Water quality – management of a natural resource. Blackwell Science, Inc. Capital City Press. Massachusetts. USA.

Pickett, S. T. A., and Mary, L. C. 2005. Vegetation dynamics. In: Eddy (ed.). Vegetation ecology. Blackwell Publishing. USA. pp 172-195

Philip, G. 1999. A reoprt on the Chokoria Sundarbans, a forest without trees. RUPANTAR October /99 issue, Khulna. Bangladesh.

Quazi, S. Mujieri, M. K., and Sajjad, Z. 1992. Land and water use in the rural setting in Bangladesh: Ipmact on the, People, Development and environment complex interlinkages in Bangladesh. IUCN, Dhaka. pp 45-55

Rahman, A. A. Saleemul, I. H., and Conway, G. R. (eds.). 1990. Environmental aspects of surface water systems of Bangladesh. University press. Dhaka, Bangladesh.

Rahman, M. A. 1990. A comprehensive report on Sundri (*Heritiera fomes*) trees with particular reference to top dying in the Sundarbans. In: Rahman, M. A., Khandakar, K., Ahmed, F. U., and Ali, M. O. (eds.). Proceedings of the seminar on top dying of *Heritiera fomes* trees held on 11 August. 1988. BARC, Dhaka. pp 12-63

Rahman, M. A. 1995. Integrated resources development of the Sundarbans reserved forest – Bangladesh- Mangrove plant pathology of the Sundarbans reserve forest in Bangladesh, UNDP, FAO, BGD/84/056 Field document 3 , UNDP and FAO, Khulna.

Rahman, A. 1995. Shrimp culture and environment in the coastal region. BIDS. Dhaka, Bangladesh

Rahman, A. (ed.). 2003. Paribesh patra (Bengali) development magazine, issue 3, 4 October-December 2002 and January-March 2003. Unnayan Shamunnay, Dhaka, Ministry of Environment and forest and UNDP.

Rahman, A., and Chowdhury, F. (eds.). 2001. ECOFile periodical on life and nature. The Sundarbans a dismal picture. Vol. IV no .4 January-March. A Shamunnay publication, supported by UNDP under SEMP. Dhaka.

Rahman, M., and Petersen, L. (eds.). 2001. Soil resources in Bangladesh: Assessment and Utilisation. Proceedings of the annual workshop on soil resources, 14-14 February. Soil Resources Development Institute (SRDI), Prokash Mudrayan, Dhaka.

Rahman, M. A. 2001. Top dying of Sundri (*Heritiera fomes*) trees in the Sundarbans; Extent of damage. Paper presented at the 1st national conference on the Sundarbans at university of Khulna, 14 -16 February, Khulna.

Rahman, A. 2001. Diseases and disorders of tree species in the Sundarbans and their management. In: Siddiqi, and Baksha (eds.). Proceedings of the national workshop on mangrove research and development in Bangladesh. BFRI, Chittagong. pp 86-97

Ramsar Bureau, 2005. The world heritage convention, cultural landscapes and wetlands – The Ramsar bureau convension of wetlands website: http:// www.ramsar.org /2005

Rashid, S. M. A. Khan, A., and Akanda, A, W. 1994. Fauna. In: Hussain, Z. Acharya, G. (eds.). Mangrove of the Sundarbans. IUCN, Bangkok. pp 115-132

Razaque, A. 1981. Study on hydrolic conductivity and dispersion of clay collides in columns. PhD thesis at Ghent University, Belgium.

Rob, A. 1997. The endangered Sundarbans: Studies in mangroves environment. The weekly Independent, 20th June 1997. Dhaka. pp 5-7

Rössler, M. 2000. Landscape stewardship: new directions in conservation of nature and culture, world heritage cultural landscapes – The George Wright FORUM, Volume 17. No. 1, 2000. Paris, France.

Rull, V. 1998. Evalucion de los manglares neotropicales: La crisis del ecoceno. Interciencia 23: 355/362

Sharafuddin, A. M. 1992. Awareness and public participation in wetland management. National workshop on conservation and sustainable management of freshwater wetland in Bangladesh, Dhaka: GOB, CIDA and IUCN, 9-11 December.

Saha, S. K, Datta, D. K., and Rahman, M. S. 2001. Origin of the Sundarbans: A bioclimatological study. Paper presented at the 1st national conference at University of Khulna, 14-16 February, Khulna.

Sakamoto, M. Hagihara, Y., and Hoque, B. A. 2001. Time Series Model analysis of the conflict over the Ganges water resources between Bangladesh and India. Graduate School of Civil Engineering Systems. Kyoto University. Japan.

Salar, A. Haq, E. Atik, R. Rashid, S., and Ahmed, H. (eds.). 1994. Wetlands of Bangladesh. Bangladesh Centre for Advance Studies and Nature Conservation Movement. Dhaka.

Salomons, W. (ed.). 1999. Perspectives on integrated coastal zone management, Springer-Verlag Berlin, Germany.

Salter, R. E. 1987. Status and utilisation of wildlife: Food and Agricultural Organisation, Rome, Italy.

Sarker, S. U. 1992. Ecology of wildlife. UNDP/FAO/BGD/ (5/011. Field document No. 50. IFCU.

Seidensticker, J., and Hai, M. A. 1983. The Sundarbans wildlife management plan, conservation in the Bangladesh coastal zone. IUCN, Gland. Switzerland.

Semeniuk, V. 1983. Mangrove distribution in north Western Australia in relationship to regional and local freshwater seepage. Vegetation, 53: pp11-31

Sharmila, D. 1989. Environmental Character and Planning Prospect of Sundarbans. In: Jafar, R. K. (ed.). Journal of the Bangladesh National Geographical Association. Department of Geography. JU, Savar, Dhaka. Vol. 17 Nos. 1 & 2. pp 13-25

Siddiqi, N. A. 1992. Regeneration status and influence of animals on regeneration in the Sundarbans mangrove forests. PhD thesis, Department of Zoology, University of Dhaka.

Siddiqi, N. A. 1994. The importance of mangroves to the people in the coastal areas of Bangladesh. Proceedings VII Pacific Science International Congress, Mangrove Session organised by International Society for Mangrove Ecosystems (ISME), Okinawa, 1-2 July 1993, Japan.

Siddiqi, N. A. 2001. Mangrove forestry in Bangladesh. Institute of Forestry and Environmental Sciences, University of Chittagong. Nibedon Press Limited, Chittagong.

Siddiqi, N. A. 2001a. Mangroves of Bangladesh Sundarbans and Accretion Areas. In: Lecerda, D. D. L. (ed.). Mangrove ecosystems function and management. Springer-Verlag Berlin. pp 142- 258- 292

Siddiqi, N. A., Islam, M. R., and Khan, M. A. S. 1989. Effect of salinity on germination success in Keora (*Sonneratia apetala Buch-Ham*) Seeds. Bano Biggyan Patrika. Chittagong, Bangladesh 18. pp 9-63.

Siddiqi, N. A., and Das, S. 2000. The Mangroves and mangrove forests of Bangladesh. Mangrove silviculture division bulletin 2. Bangladesh Forest Research Institute. Chittagong.

Siddiqi, N. A., and Baksha, M. W. (eds.). 2001. Mangrove research and development. Proceedings of the National workshop on Mangrove Research and Development at Bangladesh forest Reserach Institute, 15-16 May, Chittagong.

Sobhan, A. 1973. Report on the preliminary investigation of probable causes of top-dying of Sundri trees in the Sundarbans, unpublished report - Soil science division, BFRI, Chittagong, Bangladesh.

SRDI-(Soil Resource Development Institute), 2000. Soil salinity in Bangladesh. Soil Resource Development Institution, Farmgate, Dhaka, Bangladesh.

SBCP- (Sundarbans Biodiversity Conservation Project), 1997. Biodiversity Conservation in the Sundarbans Reserve Forest. ADB, PPTA No. 2724-BAN. Mid-term options report. Anzdel limited/ Eusuf and Associated. Dhaka.

SBCP-(Sundarbans Biodiversity Conservation Project), 2000. Sundarbans Biodiversity Conservation Project. Inception report Vol. 1, Project report no. 2 ADB: BAN 1643/3158. June 2000 ADB, GEF and the Netherlands Government.

Smith, R. L., and Smith, T. M. (eds.). 2003. Elements of ecology 5th edition. Benjamin Cummings, New York. PP-397 –594

Tilley, C. 1994. Places, Paths and monuments - A phenomenology of landscape. Oxford - Providence, USA.

Tomlinson, B. P. 1986. The botany of mangrove. Cambridge University Press. London. UK

Turner, M. I. 2001. The ecology of trees in the tropical rain forest. Cambridge University Press. UK.

Turner, R. K. Batemar, I. J., and Adger, W. N. (eds.). 2001. Economics of coastal and water resources: Valuing environmental functions. Studies in ecological economics volume 3. Kluwer Academic Publisher, The Netherlands. pp 1-43

Umitsu, M. 1997. Landforms and floods in the Ganges delta and coastal lowland of Bangladesh, Marine Geodesy. 20 (1). pp 76 –87

UNDP, 2000. Participatory rural appraisal - practical handbook-Thana cereal technology transfer and identification project. (GOB/ UNDP/FAO project: BGD/89/045) Government of the People's Republic of Bangladesh. Ministry of Agriculture, Department Agricultural Extension. Dhaka.

UNESCO, 1962. Recommendation concerning the safeguarding of the beauty and character of landscapes and sites. Paris. France

UNESCO, 1992. Workshop on coastal zone management in Bangladesh. 27-31 December. Bangladesh National Commisstion for the UNESCO. Dhaka

UNESCO, 1999. Operational guidelines for the implementation of the World Heritage Convention. World Heritage Centre. UNESCO, Paris. France

UNESCO, 2001. Properties inscribed on the world heritage list-UNESCO 1972 convention concerning the protection of the world centre, Paris. France.

Vogt, K. A. Gordon, J. C. Wargo, J. P. Vogt, D. J. Heidi, A. Peter, A. P. Clark, H. J. Hara, J. L. O. Keaton, W. S. Weznand, T. P., and Witten, E. (eds.). 1996. Ecosystems- Balancing Science with Management. Springer, New Haven, USA.

Wahid, S. M. 1995. Hydrological study of the Sundarbans. UNDP/FAO project BGD/84/056, Department of Forest, and Dhaka, Bangladesh. pp 16-34

White, I. 2005. Hydrology. In: Grafton, R. Q. Robin, L., and Wasson, R. (eds.). Understanding the environment - bridging the disciplinary divides. UNSW Press and CAER, Sydney. Australia.

WTO - (World Tourism Organisation), 2002. The economic impact of tourism in the islands of Asia and the pacific. A report on the WTO international conference on Tourism and island economics 13-15 June. WTO, Madrid, Spain.

Water and conflict in Asia/1999
http:// www.apcss.org/Report_water% 26 conflict_99.html.

Wijmstra, F. A. 1969. Palynology of the Alliance well. Geol Mijnbouw 48: 125 -133

Zube, E, H. 1986. Landscape values: History, concepts and applications. In: Smardon, Palmer., and Felleman (eds.). Foundations for Visual project analysis. John Wilay + Sons, New York. pp 4-19

Appendix 1

World Mangroves Distribution in km²

The total area of the world mangroves are 181,327 km^2 until 1997. According to the region Mangrove classification can be categorised into 6 regions such as Asia excluding Middle East 75,172.8 km^2, Central America and Caribbean- 22,759.5 km^2, Middle East and Africa 1,492.0 km^2, North America 1,990.0 km^2, South America 24,084.0 km^2 Sub-Saharan Africa 36,512.3 km^2 and developing countries 167,006.6 km^2.

Name of the Country	**Area in km^2**	**Name of the Country**	**Area in km^2**
1. Angola - AGO	1,250	20. Congo, Dem. Rep.	226
2. Antigua and Barbuda	13.2	21. Costa Rica	370
3. Aruba- ABW	4.2	22. Cöte d‘ Ivore	644
4. Australia	11,500	23. Cuba	7,848
5. Bahamas	2,332	24. Djibouti	10
6. Bahrain	1	25. Dominica	1.6
7. Bangladesh	6017	26. Dominica Rep.	325
8. Barbados - BRB	0.1	27. Ecuador	2,469
9. Belize -BLZ	719	28. Egypt	861
10. Benin- BEN	17	29. El Salvador	268
11. Bermuda- BMU	0.1	30. Equatorial Guinea	277
12. Brazil	13,400	31. Fiji	385
13. Brunei Darussalam	171	32. French Guiana	55
14. Cambodia	851	33. Gabon	2,500
15. Cameroon	2,494	34. Gambia	497
16. China	366	35. Ghana	100
17. Colombia	3,659	36. Grenada	2.4
18. Comoros	26.2	37. Guadeloupe-GLP	39.8
19. Congo	120	38. Guatemala	161
39. Guinea	2,963	70. Philippines	1,607
40. Guinea -Bissau	2,484	71. Puerto Rico- PRI	92

41. Guyana	800	72. Qatar	5.0
42. Haiti	134	73. Samoa- WSM	7
43. Honduras	1,454	74. Saudi Arabia	292
44. Hong-Kong	2.8	75. Senegal	1,853
45. India	6,700	76. Seychelles -SYC	29
46. Indonesia	42,550	77. Sierra Leone	1,838
47. Iran	207	78. Singapore	6
48. Jamaica	106	79. Solomon Islands	642
49. Japan	4	80. Somalia	910
50. Kenya	530	81. South Africa	11
51. Liberia	190	82. Sri Lanka	89
52. Madagascar	3,403	83. St. Lucia - LCA	1.3
53. Malaysia	6,424	84.St.Vincent Grenadines	0.5
54. Martinique -MTQ	15.9	85. Sudan	937
55. Mauritania	1	86. Suriname	1,150
56. Mexico	5,315	87. Tanzania	1,155
57. Micronesia, Fed States	86	88. Thailand	2,641
58. Mozambique	925	89. Togo- TGO	26
59. Myanmar	3,786	90. Tonga - TON	10
60. Netherlands Antilles	11.4	91. Trinidad & Tobago	70
61. Caledonia - NCL	456	92. UAE	30
62. New Zealand	287	93. United States	1,990
63. Nicaragua	1,718	94. Vanuatu - VUT	16
64. Nigeria	10,515	95. Venezuela	2,500
65. Oman	20	96. Viet Nam	2,525
66. Pakistan	1,683	96. Virgin Islands	9.8
67. Panama	1,814	97. Yemen	81
68. Papua New Guinea	5,399	**Total**	**181,327**
69. Peru	51		

Source: Man, land and sea-coastal resource use and management in Asia and the Pacific, 1992

Appendix 2

Mangrove Species (Trees, shrubs and herbs) in the Sundarbans in Bangladesh

Scientific Name	Family	Vernacular Name	Type of Plant
1. *Acanthus ilicifolius*	Acanthaceae	Hargoza	Scrambling, thomy herb
2. *Acrostichum aureum*	Pteridiaceae	Tiger fern/ Udoban	Gregarious fern
3. *Agaialitis rotundifolia*	Plumbaginaceae	Dhalchaka	Small tree
4. *Aegiceras corniculatum*	Myrsinaceae	Khalisha, khalshi	Shrub
5. *Amoora cucullata*	Meliaceae	Amur	Small tree
6. *Avicennia alba/marina*	Avicenniaceae	Morcha baen/sada baen	Small tree
7. *Avicennia officinalis*	Avicenniaceae	Baen	Tree
8. *Barringtonia racemosa*	Barringtoniaceae	Kumb, Kumba	Small tree
9. *Blumea species*	Compositae	Bari a gash, bongash	Aromatic herb
10. *Brownlowia tersa*	Tiliaceae	Lota Sundri	Scandent shrub
11. *Bruguiera gymnorrhiza*	Rhizophoraceae	Kankra	Tree
12. *Caesalpinia crista*	Leguminosae	Kutum katta	Armed shrub
13. *Cerbera manghas*	Apocynaceae	Dagor	Small tree
14. *Ceriops decandra*	Rhizophoraceae	Goran	Shrub or small tree
15. *Clerodendrum inerme*	Verbenaceae	Sitka , sitki	Scandent shrub
16. *Cynometra ramiflora*	Leguminosae	Shingra	Shrub
17.*Cyperus javanicus*	Cyperacea	Kucha, Kusha	Grass
18. *Dalbergia candenatensis*	Leguminosae	Chanda lota	Scrambling climber
19. *Dalbergia spinosa*	Leguminosae	Chanda katta	Scandent, armed shrub
20. *Dendrophthoe falcata*	Loranthaceae	Porgassa	Parasite in tree crowns
21. *Derris trifoliata*	Leguminosae	Gila lota, Kali lota	Climber
22. *Diospyros peregrina*	Ebenaceae	Gaeb	Tree
23. *Drypetes species*	Euphorbiaceae	Achet	Scandent shrub
24. *Eriochloa procera*	Gramineae	Nolgash	Grass
25. *Eugenia fruticosa*	Myrtaceae	Ban jam, jam gach	Small tree
26. *Excoecaria agallocha*	Euphorbiaceae	Gewa	Tree
27. *Excoecaria indica*	Euphorbiaceae	Batla, batul	Small tree
28. *Ficus Species*	Moraceae	Jir	Tree with aerial roots
29. *Flagellaria indica*	Flagellariaceae	Abetaa	Climber
30. *Flueggia virosa*	Euphorbiaceae	Sitka, sitki	Scandent shrub
31. *Heritiera fomes*	Sterculiaceae	Sundri	Tree
32. *Hibiscus tiliaceous*	Malvaceae	Bhola	Shrub

33. *Hoya species*	Asclepiadaceae	Agusha	Climber
34. *Imperata cylindrica*	Gramineae		Grass
35. *Intsia bijuga*	Leguminosae	Bhaela, Bharal	Small tree
36. *Ipomoea pes-caprae*	Convulvulaceae		Succulent, herb
37. *Ixora species*	Rubiaceae	Bon bakul	Small tree
38. *Kandelia candel*	Rhiyophoraceae	Gura, guae, gural	Small tree
39. *Leea aequta*	Leeaceae		Shurb
40. *Lepisanthes rubiginosa*	sapindaceae	Bon lichu	Tree
41. *Lap.Nov. aff. rubiginosa*	sapidaceae		Shrub
42. *Lumnitzera racemosa*	Combretaceae	Kirpa, Kripa	Small tree
43.*Macrosolen cochinchinensis*	Loranthaceae	Poragassa	Parasite in tree crowns
44. *Mallotus repandus*	Euphorbiaceae	Bon notoy	Scandent shrub
45. *Macuna gigantea*	leguminosae	Doyal	Climber
46. *Myriostachya wightiana*	Gramineae	Dhanshi	Grass, new accretions
47. *Nypa fruticans*	Plamae	Golpata	Plam , underground stem
48. *Pandanus foetidus*	Pandanaceae	Kewa Katta	Prickly succulent screw
49. *Petunga roxburghii*	Rubiaceae	Narikili	Small tree
50. *Phoenix paludosa*	Palmae	Hantal	Thorny palm
51. *Phragmites Karka*	Gramieae	Nol kagra	Grass
52. *Pongamia Pinnata*	Leguminosae	Karanj, Karanja	Small tree
53. *Premna corymbosa*	Verbenaceae	Serpoli, setpoli	Shrub or small tree
54. *Rhizophora mucronata*	Rhizophoraceae	Garjan, Jhanna	Tree with stilt roots
55. Salacia chinensis	Calastraceae	Choyt barai	Small tree
56. *Sarcolobus globosus*	Asclcpiadaceae	Bowali lota	Climber
57. *Sonneratia caseolaris*	Sonneratiaceae	Choyla, ora, soyla	Small tree
58. *Sonneratia apetala*	Sonneratiaceae	keora	Tree
59. *Stenochlaena palustris*	Blechnaceae	Deki lota	Climbing fern
60. *Tamarix indica*	Tamaricaceae	Jhao, nonajhao	Small tree
61.*Tetrastigma bracteolatum*	Vitidiaceae	Golgoti lota	Climber
62. *Thunbergia species*	Thunbergiaceae	Jermani lota	Climber
63. *Viscum monoicum*	Loranthaceae	Shamu lota	Woody parasite in tree
64. *Xylocarpus granatum*	Meliaceae	Dhundul	Small tree
65. *Xylocarpus mekongensis*	Meliaceae	Passur	Tree

Source: Chaffey and Sandom, 1985; Siddiqi 2001, pp 36-37

Appendix 3

The main species of mangroves in South America, Africa and Eastern Tropics according to Morley (2000) based on regional climate and availability of species.

South and Latin America	**West/ East Africa**	**Eastern Tropics**
Mangroves	**West Africa**	**Mangroves**
*Avicennia * bicolor*	**Mangroves**	*Avicennia * alba*
*Avicennia * germinas*	*Avicennia * germinans*	*Avecennia * eucalyptifolia*
*Pelliciera rhizophora **	*Rhizophora * mangle*	*Avecennia * intermedia*
*Phizophora *mangle*	*Rhizophora * racemosa*	*Avecennia * marina*
Rhizophora x harrisonii*	*Rhizophora * x harrisonii*	*Avecennia * officinalis*
*Rhizophora * racemosa*		*Bruguiera + cylindrica*
	Backmangroves	*Bruguiera + exaristata*
Backmangroves	*Acrostichum * aureum*	*Bruguiera + gymnorrhiza*
*Acrostichum * aureum*	*Conocarpus erectus*	*Bruguiera + hainsii*
Conocarpus erectus	*Laguncularia racemosa*	*Bruguiera + parviflora*
Laguncularia racemosa		*Bruguiera + sexangula*
Pterocarpus officinalis	**East Africa**	*Ceriops + decandra*
	Mangroves	*Kandelia + candel*
	*Avicennia * marina*	*Lumnitzera ** littorea*
	Bruguiera + gymnorrhiza	*Lumnitzera ** racemosa*
	*Rhizophora * mucronata*	*Rhizophora * apiculata*
	*Sonneratia alba **	*Rhizophora* mangle*
		Rhizophora mucronata*
	Backmangroves	*Rhizophora * racemosa*
	Acrostichum aureum*	*Rhizophora * stylosa*
	Ceriops + tagal	*Sonneratia alba**
	Heritiera littoralis	*Sonneratia apetala**
	*Pemphis * acidula*	*Sonneratia griffithii**
	Xylocarpus granatum	*Sonneratia ovata **
		Backmangroves
		*Acanthus ebracteatus**
		*Acanthus ilicifolius **
		*Acrostichum * aureum*
		Acrostichum speciosum*
		*Aegialitis * annulata*
		*Aegialitis * rotundifolia*
		*Aegiceras * corniculatum*
		*Brownlowia * argentata*
		*Camptostemon * philippinense*
		*Camptostemon * schultzii*
		Cerbera odallum
		Cerbera manghas
		Derris uliginosa

		*Excoecaria *agallocha*
		Ficus retusa*
		*Heritiera * littoralis*
		Hibicus tiliaceus*
		*Intsia * bijuga*
		*Nypa fruticans**
		*Oncosperma * filamentosa*
		Osbornia octodonta
		Scyphiphora hydrophyllacea
		*Sonneratia caseolaris**
		*Thespesia populnea**
		Xylocarpus granatum
		Xylocarpus mekongensis

Source: Morley, 2000, pp 22-23

Note: The main species of mangroves in South America, Africa and the Eastern tropics, with an indication (*) as to the occurrence of their pollen in the fossil record. The pollen of genera of *Rhizophoraceae* (marked +) is very similar to the *Rhizophora*; pollen of *Lunmnitzera* (marked **) is similar to many other combretaceae, and also Melastromataceae. The position of the asterisk indicates whether pollen determination is at the generic or specific level.

Appendix 4

The important mangrove wildlife species in the Sundarbans mangrove forest in Bangladesh

Amphibians family	**Common Name**	**Scientific Name**
Bufonidae	Common Toad	*Bufo melanostictus*
Microphylidae	Ornate Microhylid	*Microhyla ornata*
Ranidae	Skipper Frog	*Euphlyctis cyanophlyctis*
	Green Frog	*Euphlyctis hexadactylus*
	Bull Frog	*Hoplobatrachus tigerinus*
	Cricket Frog	*Limnonectes limnocharis*
	Boulenger's Frog	*Rana alticola*
Rhacophoridae	Common Indian Tree Frog	*Polypedates maculatus*
Reptiles family		
Agamidae	Garden Lizard	*Calotes jerdoni*
Gekkonidae	Common House Lizard	*Hemidactylus frenatus / flaviviridis*
	House Lizard	*Hemidactylus brookii*
	Wall Lizard	*Gekko gecko*
Varanidae	Bengal Monitor	*Varanus bengalensis*
	Yellow Monitor	*Vranus flavescens*
	Ring Lizard	*Varanus salvator*
Scincida	Common Skink	*Mabuya carinata*
Cheloniidae	Olive Ridley turtle	*Lepidochelys olivacea*
	Green Turtile	*Chelonia mydas*
	Loggerhead Turtle	*Caretta caretta*
	Hawksbill turtle	*Eretmochelys imbricata*
Trionychidae	Spotted Flapshell Turtle	*Lissemys punctata*
	Ganges Softshell Turtle	*Aspideretes gangeticus*
	Asiatic Softshell Turtle	*Chitrra indica*
	Peacock Softshell Turtle	*Aspideretes hurum*
	Bibron's Softshell Turtle	*Pelochelys bibroni*
Bataguridae	Indian Roofed Turtle	*Kachuga tecta*
	River Terrapin	*Batagur baska*
	Yellow turtle	*Morenia petersi*
	Three-keeled Land tortoise	*Melanochelys tricarinata*
Elaphidae	King Cobra	*Ophiophagus hannah*
	Binocellate cobra	*Naja naja*

	Belgal Cobra	*Naja Kaouthia*
	Common Ktait	*Burgarus caeruleus*
	Banded Krait	*Bungarus fasciatus*
Hydrophidae	Hook-nosed Sea Snake	*Enhydrina schistosa*
	Black- headed Sea Snake	*Hydrophis nigrocinctus*
	Estuarine Sea Snake	*Hydrophis obscurus*
	Malacca Sea Snake	*Hydrophis caerulescens*
	Common Narrow-headed Sea Snake	*Microcephalophis gracilis*
	Cantor's Narrow-headed Sea Snake	*Microcephalophis cantoris*
Natricidae	Checkered Keelback	*Xenochrophis piscator*
	Dark-bellied Marsh Snake	*Xenochrophis cerasoggaster*
	Stripped Keelback	*Amphiesma stolata*
	Olive keelback	*Atretium schistosum*
Homalopsidae	Glossy Marsh Snake	*Gerardia prevostianus*
	Common Smooth Water Snake	*Enhydris enhydris*
	White –bellied Mangrove snake	*Fordonia leucobalia*
	Dog –Vaced Water Snake	*Cerberus rhynchops*
Colubridae	Rat Snake	*Coluber mucosus*
	Common Vine Snake	*Ahaetulla nasutus*
Boidae	Common Sand Boa	*Eryx conica*
	Rock Python	*Python molurus*
Viperidae	Russell's Viper	*Vipera russellii*
	Spot-tailed Pit Viper	*Trimeresurus erythrurus*
Typhlopidae	Slender Worm Snake	*Typhlops porrectus*
	Common Worm Snake	*Ramphotyphlops braminus*
Dipsadidae	Common wolf Snake	*Lycodon aulicus*
Acrochordidae	Wart Snake	*Acrochordus granulatus*
Crocodylidae	Estuarine Crocodile	*Crocodylus porosus*
Mammals Family		
Soricidae	Grey Musk Shrew	*Suncus murinus*
	Common Tree Shrew	*Tupaia glis*
	Flying Fox	*Pteropus giganteus*
	Short-nosed Fruit Bat	*Cynopterus sphinx*
	Fulvous Fruit Bat	*Rousettus leschenaulti*
Rhinopomatidae	Lesser Rat-tailed Bat	*Rhinopoma hardwickii*
Megadermatidae	False Vampire	*Megaderma lyra*

Hipposideridae	Tailless Leaf-nosed Bat	*Coelops frithii*
Vespertilionidae	Indian Pipistrelle	*Pipistrellus coromandra*
	Indian Pigmy Pipistrelle	*Pipistrellus mimus*
	Greater Yellow Bat	*Scotophilus heathii*
	Asiatic Lesser Yellow Bat	*Scotophilus kuhlii*
Cercopithecidae	Rhesus Macaque	*Macaca mulatta*
Felidae	Bengal Tiger	*Panthera tigris*
	Jungle Cat	*Felis chaus*
	Leopard Cat	*Prionailurus bengalensis*
	Fishing Cat	*Prionailurus viverrinus*
Canidae	Jackal	*Canis aureus*
	Bengal Fox	*Vulpes bengalensis*
Herpestidae	Small Indian Mongoose	*Herpestes auropunctatus*
	Common Mongoose	*Herpestes edwarsi*
Mustelidae	Smooth-coated Otter	*Lutra perspicillata*
	Clawless Indian Civet	*Aonyx cinerea*
Viverridae	Large Indian Civet	*Viverra zibetha*
	Small Indian Civet	*Viverricula indica*
	Common Palm Civet	*Paradoxurus hermaphroditus*
Suidae	Wild Boar	*Sus scrofa*
Cervidae	Spotted Deer	*Cervus axis*
	Barking Deer	*Muntiacus muntjak*
Sciuridae	Fivestripped Palm Squirrel	*Funambulus pennanti*
Muridae	Bandicoot Rat	*Bandicota indica*
	Lesser Bandicoot Rat	*Bandicota bengalensis*
	House Mouse	*Mus musculus*
	Common House Rat	*Rattus rattus*
	Long-tailed Tree Mouse	*Vandeleuria oleracea*
Hystricidae	Indian Porcupine	*Hystrix indica*
Leporidae	Rufouse-tailed Hare	*Lepus nigricollis*
Dolphinidae	Common Dolphin	*Delphinus delphis*
	Irrawaddy Dolphin	*Orcaella brevirostrus*
	Indian Pilot Whale	*Globicephala marcrorhynchus*
	Melon-headed Dolphin	*Reponocephala electra*
Phoceonidae	Little Porpoise	*Neophocaena phocaenoides*
Platanistidae	Ganges River Dolphin	*Platanista gangetica*

Source: Chowdhury, IUCN 2001 pp 149-150

Appendix 5

There are 430 rivers, creeks and canals have been made great network systems in this deltaic mangrove region. The river water body covers around 2000 km² (175686 hectares) area in the Sundarbans. The major rivers and canals/ creeks are showing in the following table.

Potential Rivers	Creeks/ Canals	Creeks/ Canals
1. Agargotta river	1. Chilabogi	52. Tetulbaria
2. Arpongasia river	2. Nishanbari	53. Hishamari
3. Andharmanik river	3. Jhapai	54. Horikali
4. Badamtola river	4. Karomjal	55. Charputia
5. Bhola river	5. Jongra	56. Chotlathimara
6. Baleswar river	6. Morapassur	57. Adanibaroburi
7. Bhangra river	7. Surjamukhi	58. Kalirkhal
8. Betmar river	8. Padmaboti	59. Nishankhali
9. Cunar river	9. Signboard	60. Kastura
10. Chorabetmar river	10. Nandabala	61. Mochrashing
11. Chaloki river	11. Tanbulbunia	62. Mollarkhali
12. Chukuni river	12. Bhaijhora	63. Hoddakhal
13. Deboki river	13. Kewcharkhal	64. Fultala
14. Dhumkoli river	14. Morjurbaria	65. Joymoni
15. Dutmukhi river	15. Aruaband	66. Gewakhali
16. Dingimari river	16. Patakata	67. Jhaka
17. Isamati river	17. Charbetmar	68. Chorerkhal
18. Firingi river	18. Chottosundara	69. Aloki
19. Harintana river	19. Sabrakhali	70. Chotsheali
20. Harinbhangha river	20. Chechaing	71. Shelonkhali
21. Hangsharaj river	21. Khormakhali	72. Sonakhali
22. Jamuna river	22. Andharmanik	73. Mandarbari
23. Jhalokati river	23. Bojobojha	74. Indirakani
24. Jafa river	24. Khejura	75. Sundarikouta
25. Kaira river	25. Bhedakhali	76. Chotkukumari
26. Kalagachi river	26. Dhublakhali	77. Pasuurtala
27. Kobadak river	27. Barosheali	78. Gewakhali
28. Kalindini river	28. Khashitana	79. Kalabogi
29. Kasitana river	29. Jhapa	80. Dobeki
30. Kesonkhali river	30. Kalaboga	81. korulia

31. Kholpetua river	31. Bushianga	83. Selnakhali
32. Mara river	32. Bhomorkhali	84. Nilkamalbhorani
33. Meghna river	33. Borokukumari	85. Sechkhali
34. Mrigamari river	34. Putia	86. Kukushia
35. Mortaj river	35. Sutarkhali	87. Nakjora
36. Meghua river	36. Sarbatkhali	88. Latabeki
37. Buramortaj river	37. Sakbaria	89. Kachikata
38. Passur river	38. Baintalarbharani	90. Mathbhanga
39. Pathuria river	39. Jhanjhania	91. Borobaikari
40. Ardpangasia river	40. Kumarkati	92. Hilchar
41. Pakusta river	41. Chaulabogi	93. Khejurdana
42. Raimangal river	42. Belmari	94. Dengibari
43. Sakbaria river	43. Kodalia	95. Kalagasia
44. Sela river	44. Sitakotka	96. Charkhali
45. Sund-Jhajhap	45. Gaberkhal	97. Bishanbari
46. Sibsa river	46. Chottokalijhira	96. Atharobeki
47. Arua sibsa river	47. Boro kalijhira	98. Chunkuri
48. Sutarkhali river	48. Tigerpoint khal	99. Boikari
49. Bal river	49. Kochikhali	100. Bodrashena
50. Nilkomal river	50. Jalkata	101. Agunjala
51. Notabaki river	51. Beki	102. Boro Kathka

Source: Ahmed, 2001; IUCN-1994 and SBCP-IWM, 2003