Development of Decision Aid for Ecohydrological Consideration in Flood Management in Deltaic Floodplain

by

Sultan Ahmed

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This is to certify that this work entitled "**Development of Decision Aid for Ecohydrological Consideration in Flood Management in Deltaic Floodplain"** has been done by me under the supervision of Dr A K M Jahir Uddin Chowdhury, Professor of Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET), Dhaka. I do hereby declare that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma from any other institution.

Signature of the candidate

____

Sultan Ahmed

DEDICATION

To my parents, (*Late*) Kashem Ali Munshi and Jahan Ara Begum, who did not force me in household chores or agricultural duties, rather allowed me unlimited freedom in my childhood.

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ABSTRACT

Traditional flood management interventions adversely affect floodplain ecosystem as they do not maintain flood flow vital for preserving the floodplain ecosystem. Flood management intervention needs to be planned and implemented considering ecohydrological criteria to sustain floodplain ecosystem. Consideration of ecohydrological criteria in flood management can restore or preserve the ecosystem of a deltaic floodplain. This study has developed a decision aid framework for determination of flood management option and regulation which consider both ecological and hydrological criteria in planning flood management intervention in deltaic floodplain. The study introduces a term 'ecohydrograph' that combines hydrological requirement of the floodplain ecological community with respect to seasonality, and implementation of which will help sustain the floodplain ecosystem. A simple decision aid framework has been developed that gives, as an output, an eco-friendly flood management infrastructure and operation rules for flow control structures corresponding to the ecohydrograph. Implementation of the ecohydrograph will reestablish a hydrological environment in a modified or damaged floodplain, which will support living system of the biotic community of the floodplain.

Flood flow characteristics that are vital for ecosystem sustenance *ie* hydrological indicators such as time of rise, depth, extent, duration, time of recession and frequency of flood, runoff of the floodplain have been determined from hydrologic literature review. Similarly ecological indicators such as floral and faunal diversity, water depth and time preferences of floodplain fish species for spawning migration, incubation and breeding, habitat opportunity for living and feeding, and time of out-migration have also been determined from literature review. Thus a range of hydrological and ecological indicators suitable for ecological resources have been identified and an indicator based relationship between hydrology and ecology has been developed for round the year from January to December comprising flood-cycle *ie* hydrograph, fish life-cycle and paddy crop-cycle. From this relationship a hydrograph suitable for ecosystem *ie* ecohydrograph has been determined. To determine this ecohydrograph, a decision aid framework has been developed that includes hydrological and ecological datasets, ecohydrological relationship, and a 2-D hydrodynamic model for a trial and

error performance to find out the ecohydrograph and the optimum flood management option corresponding to the ecohydrograph.

An intervened area with a flood control, drainage and irrigation project being implemented since 1983 has been selected for the study. Hydrological data of floodplains are not available because there is no practice of collecting floodplain hydrological data in Bangladesh. Hydrological data of the study area floodplain for pre-project condition have been generated using 2-D overland flow hydrodynamic model. Ecological data have been collected using social survey techniques of key informant interview (KII), focus group discussion, and sampling and market survey. Impacts on hydrology and ecosystem have been assessed from data analysis.

The decision aid framework has been applied to the study area. The ecohydrograph and the corresponding optimum flood management option have been determined using the 2-D hydrodynamic model of the decision aid framework through a trial and error process by changing time and regulating water levels of the canals. The ecohydrological status/indicators at optimum flood management option have been assessed and found close to those of the pre-project period. A comparative picture of hydrological and ecological estimates of the study area for pre-project and post-project periods and after reestablishment of the optimum flood management option corresponding to the ecohydrograph has been estimated. The connectivity between the river and the study-area-floodplain and average water depth in the study area increase significantly. Fish habitat increases by 57% and fish production increases from 53.3 MT in the post-project period to 99.2 MT in the optimum ecohydrograph option; while only 3.34% Aman production is reduced. Biodiversity which was reduced to 19 in the post-project period from 48 in the pre-project period reaches at 35; while ‘high’ species dominance in the post-project period improves to ‘moderate’.

If the decision aid framework is applied to the existing FCDI projects and the ecohydrograph is attained in every project then the floodplains of the country will be biologically more productive and diverse with many species. This ecohydrograph and decision aid framework would enable ecosystem approach of management of natural resources particularly water and aquatic biological resources.

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ABBREVIATIONS AND ACRONYMS

BMD	Bangladesh Meteorological Department
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CEGIS	Center for Environmental and Geographic Information Services
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EIA	Environmental Impact Assessment
FAP	Flood Action Plan
FCD	Flood Control and Drainage
FCDI	Flood Control, Drainage and Irrigation
FGD	Focus Group Discussion
GIS	Geographic Information System
GoB	Government of Bangladesh
GPS	Global Positioning System
HIL	High Inundation Level
HYV	High Yielding Varieties
IWM	Institute of Water Modelling
IWRM	Integrated Water Resources Management
KII	Key Informants Interview
MPO	Master Plan Organisation

NGO	Non Government Organisation
NWMP	National Water Management Plan
NWP	National Water Plan
NWPo	National Water Policy
NWRD	National Water Resources Database
O&M	Operation and Maintenance
PWD	Public Works Department
RS	Remote Sensing
SWR	South West Region
WARPO	Water Resources Planning Organization

Chapter 1
INTRODUCTION

1.1 Background and Present State of the Problem

Floodplain landscape performs an important environmental function by providing rich habitat for ecosystem. The floodplain water regime nurtures and maintains ecological resources of the floodplain. Alteration of flow regimes has seriously threatened ecological sustainability of rivers and floodplain wetlands (Bunn and Arthington, 2002). Traditional flood management interventions adversely affect floodplain ecosystem as they do not maintain required flood flow that is vital for preserving the floodplain ecosystem. Consideration of ecohydrological criteria in flood management can restore and preserve the ecosystem of a floodplain. Flood management intervention needs to be planned and implemented considering ecohydrological criteria to sustain floodplain ecosystem.

Flooding in low-gradient rivers has been recognised as an essential ecological interaction between river and its floodplain (Benke *et al*, 2000). The principal driving force for the existence, productivity, and interactions of the major biota in the river-floodplain systems is the flood pulse (Junk *et al*, 1989). Floodplain ecosystem process depends on the flood flow process *ie* extent, depth, timing, duration and frequency of flooding.

Floodplain wetlands are sites of high biodiversity that depend on flows from rivers. River management has reduced flooding to these wetlands, altering their ecology, and causing the death or poor health of aquatic biota (Kingsford, 2000). Changes to river flow conditions have direct consequences for the timing, magnitude and duration of floodwaters received by the river floodplains, which can result in significant, lasting changes to ecology and health of associated wetlands (Reid and Brooks, 2000). Manifold anthropogenic influences are the main cause of river habitat degradation and the rehabilitation of aquatic habitats is needed to restore good ecological status (Kiesel *et al*, 2009). Role of the flow regime as a key driver of the ecology of rivers and their associated floodplain wetlands is growingly recognised (Bunn and Arthington, 2002).

Bangladesh, the biggest deltaic floodplain of the world, is mostly formed with huge sediment deposition by the numerous tributaries and distributaries of the world's three great rivers—the Ganges, the Brahmaputra and the Meghna. About 80% of the country is featured with rivers and their floodplains (Brammer, 2002). The whole country is regularly washed by rain or flood waters. This makes the soil fertile. Numerous rivers and creeks, criss-crossed all over the country, and their flow dynamics make the land rich with huge biological resources. Most of these lands are prone to annual flooding but for crop production they are protected from flooding with flood control interventions. Flood management aims to create lands flood-free for crop production and to protect crops and homesteads from flooding as well. Flood protecting infrastructures such as embankment along the banks of the rivers constructed during the last few decades have disconnected the floodplains from the rivers and damaged the ecosystem of the floodplains of the country.

Since early sixties, Bangladesh Water Development Board (BWDB) alone has completed more than 600 flood control, drainage and irrigation (FCDI) projects all over the country mostly to increase agricultural production (MoWR, 2010). These projects have had many adverse impacts on water system and floodplain ecosystem because of inconsistent infrastructure, obstruction to fish migration and non-consideration of ecological criteria in the planning and implementation of these projects. Many of these projects have changed the flood flows to the floodplains; and the floodplain ecosystem *eg* life cycle of aquatic biota has been disturbed. Many floodplain wetlands in Bangladesh have lost hydraulic connectivity with river and shrunk and changed into seasonal water bodies as a result of flood control and drainage projects (Chowdhury, 2003). As per National Water Management Plan (NWMP), a major water management issue is the great damage done to capture fisheries by past interventions notably by flood control, drainage and irrigation works (WARPO, 2001).

The National Water Policy 1999 states that country's most environmental resources are linked to water resources and water management should protect, restore, preserve the environment and biodiversity and water bodies, and there should be no unplanned construction on riverbanks (MoWR, 1999). The National Environment Policy 1992 states that flood control measures including construction of embankment should be environmentally sound (MoEF, 1992).

Adversely affected floodplain ecosystem due to inconsistent flood management interventions may be restored by rationalising existing flood management interventions and regulating the flow controlling structures to allow flood flow suitable to the floodplain ecosystem. In new flood management interventions ecohydrological criteria can be considered to safeguard ecosystem of the floodplain. This thesis intends to develop a decision aid framework that will help consider ecohydrological criteria in flood management for maintenance of the floodplain ecosystem in deltaic floodplain.

1.2 Objectives with Specific Aims and Outcomes

Flood management intervention, particularly embankment along the bank of the river, disconnects the floodplain from the river. As a result lifecycle of the biological community of the floodplain is disturbed; floodplain ecosystem is changed and damaged. Impacts of flood management such as degradation of flow regime and reduction of biological resources are not visible shortly after the project is in operation rather they appear after some time. Flood management interventions can be rationalised introducing hydrological and ecological criteria in its planning, implementation and operation. To develop a decision support aid that would be helpful for ecohydrological consideration in flood management intervention in deltaic floodplain, the following objectives have been worked out for this study:

a. To determine the flood flow characteristics that are vital for ecosystem sustenance in deltaic floodplain
b. To develop relationship for prediction of impact of change in flood flow regime on ecological resources
c. To develop a decision aid framework for consideration of ecohydrological criteria for flood management in deltaic floodplain

The expected outcome of this research is a decision support framework that would be helpful for ecohydrological consideration in flood management in deltaic floodplain.

1.3 Study Approach

1.3.1 Methods and tools used

The flood pulse concept developed for river-floodplain systems by Junk *et al* (1989) has been studied to understand the linkage between flood flow process and the floodplain ecosystem. The flood pulse concept has been termed as the predictable advance and retreat of water from a river channel to its floodplain and the hydrological and biological interdependence between them (Junk *et al*, 1989; Bayley, 1995 in Benke *et al*, 2000). The flood pulse paradigm is currently the most comprehensive and adequate approach to explaining and measuring ecosystem productivity of a pulsed floodplain (Lamberts, 2008).

Flood flow characteristics that are vital for ecosystem sustenance have been determined. Hydrological and ecological indicators have been determined and a relationship among them has been developed. A framework has been developed to integrate hydrological and ecological criteria in flood management. Hydrological condition of the study area before and after flood management project/intervention has been generated and similarly ecological status has been determined. Impacts on land-use, hydrology and ecosystem because of flow alteration of the floodplain through flood protection measures have been assessed. Then the decision aid framework has been applied to the study area to test its efficacy. A hydrograph suitable for floodplain ecosystem, termed as an *ecohydrograph*, has been found out by regulating flood flow controlling structures with various options of water level and timing. A two-dimensional overland flow hydrodynamic model with required hydrological and ecological data sets has been run for this purpose. From this exercise, a trial and error process, an optimum flood management option that matches with the ecohydrograph *ie* fulfils the ecohydrological need of the floodplain ecosystem has been determined.

Flood management projects in Bangladesh are usually designed for a lifetime of 30 years. The project selected for the study is a 30-year old flood control, drainage and irrigation project of the BWDB. The impact of flood management on hydrology and biological resources of the project area is visible. The study area covers part of the floodplain of the Gorai-Madhumati River system which is a distributary and part of the southern floodplain of the Ganges delta in the South-western region of Bangladesh. It falls under the Agro-ecological Region of Low Ganges River Floodplain (Brammer *et al*, 1988). The specific study area is an intervened area with a flood control, drainage and irrigation (FCDI) project at Purulia-Charbhatpara implemented by the BWDB during 1981-83. It is located in the Kasiani Upazila of the Gopalgonj District and falls on the left bank of the Madhumati River. The study area is shown in Figure 1.1.

Integrated water resources management (IWRM) calls for an interdisciplinary approach of research and planning. A team of experts from the Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET) has identified some research issues, pertinent to the concept of IWRM, for three Districts of the southwestern part of Bangladesh. This research idea has been drawn from these research issues and the study area has been selected in one of these Districts. In the formulation of the research programme, the IWFM team followed a participatory approach and extensively discussed with the stakeholders—the people, farmers, fishers, water management organisations, government officials, etc—on the issues, causes and problems relating to water management projects. During the preparation of this research proposal and field survey thereafter, apart from extensive discussion with different academic researchers and practitioners, the author has discussed with many formal and informal stakeholders concerned with the impacts of water management in the study area, which has given the research an interdisciplinary demonstration.

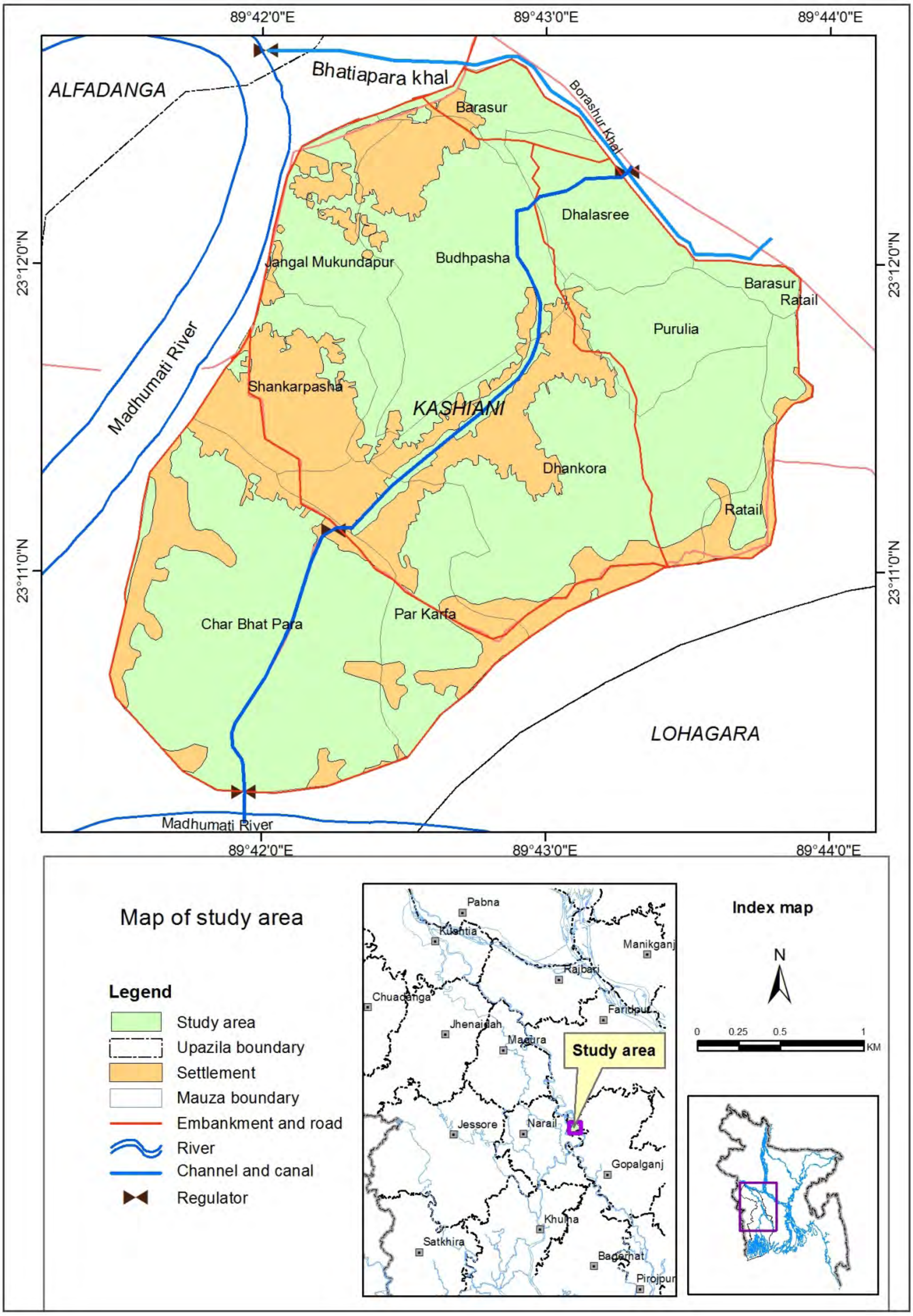

Figure 1.1 The study area

Primary data have been collected through field surveys and secondary data have been obtained from data collecting and generating agencies. Historical land records, *mouza* plot maps (1:3960) and *khatians,* of 1940s and 1980s and high resolution satellite image (1:3000) of 0.6 meter pixel size of 2007 of the study area have been obtained from the Directorate of Land Records and Surveys (DLRS) and GoogleEarth, respectively. These data have been used to determine post-project land use changes from pre-project condition taken place due to the FCDI project. River flow discharge and water level data of the Madhumati River at a station near the study area, rainfall and evaporation data at the nearby stations of the study area, river cross-section data, Purulia Char Bhatpara FCDI Project data of embankment boundary and internal canal and regulator system, and land elevation data have been obtained from the BWDB, Water Resources Planning Organisation (WARPO) and Institute of Water Modelling (IWM). Digital elevation model (DEM), which represents floodplain topography, is an essential component of a hydrodynamic model for estimation of floodplain inundation and high resolution DEM data are often desirable in predictive models (Benke *et al*, 2000). Topographic spot height data of part of the study area have been collected through field survey using electronic total station equipment to generate precise topographic surface. River bathymetry of adjacent part of the Madhumati River and digital terrain model of the study area have been developed using these data. Hydrological data of the floodplain of the study area have been generated by running one dimensional (1-D) hydrodynamic model and two dimensional (2-D) overland flow model and rainfall runoff model. Floodplain hydrographs of the study area have been prepared from these generated data. Data on fishery and agricultural practices have been obtained from the sub-district offices of the Department of Fisheries (DoF) and the Department of Agriculture Extension (DAE). Data on ecological resources (mostly various types of fish), agricultural practices, flooding in the study area before and after flood management intervention and peoples' opinion on reverting the flow regime in the floodplain have been collected through survey and interview. These ecological data have been analysed to find out changes in ecological resources of the study area that have occurred because of flood management intervention.

Geographic information system and remote sensing tools, and 1-D and 2-D hydrodynamic models have been used; and social survey like key informant interview, focus group discussion, questionnaire survey, and case study have been conducted. SOBEK 211, Mike NAM, HEC-RAS 4.0, Arc GIS 9.2, and Arc View GIS 3.3 with many extensions including HEC Geo-RAS have been used to generate floodplain hydrograph, river bathymetry and digital terrain model. Ecological data have been used to find out biodiversity and species dominance indices.

Flood flow characteristics that are vital for ecosystem sustenance *ie* hydrological indicators such as time of rise, depth, extent, duration, time of recession and frequency of flood, and runoff of the floodplain have been determined from literature review. Similarly ecological indicators such as floral and faunal diversity, time and duration of in-migration of species for spawning, incubation and breeding, habitat opportunity for living and feeding, and time of out-migration have also been determined. Thus a range of hydrological and ecological indicators suitable for ecological resources have been identified and an indicator based relationship between hydrology and ecology has been developed for the entire year from January to December comprising flood-cycle (*ie* hydrograph), fish life-cycle and paddy crop-cycle of the floodplain of the study area. From this relationship a hydrograph suitable for floodplain ecosystem *ie* ecohydrograph has been determined. To determine this ecohydrograph for the study area, a decision aid framework has been developed that includes hydrological and ecological datasets, ecohydrological relationship, and a 2-D hydrodynamic model. The ecohydrograph has been found out by running the 2-D model through a trial and error process with different water levels and timing of closing and opening of flow controlling gates, and accordingly the optimum flood management option corresponding to the ecohydrograph has been determined.

Hydrological data of floodplains are not available because there is no practice of collecting floodplain hydrological data in Bangladesh. For this reason hydrological status ie hydrograph of the floodplain of the study area in natural condition *ie* pre-project period has been generated using 2-D overland flow hydrodynamic model. Later in the post-project period the study area has been fully disconnected from the river because of the closure of the canal and the regulators. Presently, rainfall is the only source of water in the study area. For this reason a rainfall runoff model has been used to generate hydrograph of the floodplain for the post-project period *ie* for the present period. Ecological data has been collected using social survey techniques of key informant interview (KII), focus group discussion, and market survey. Hydrological and ecological changes between pre-project and post-project periods, *ie* impacts on hydrology and ecosystem, have been estimated from data analysis.

The decision aid framework has been applied to the study area. Considering the case that optimum flood management intervention has been reestablished in the study area, the ecohydrograph and the corresponding optimum flood management option and the hydrological status of the floodplain of the study area have been determined using the 2-D hydrodynamic model of the framework through a trial and error process for different water levels in the canals and time of closing and opening of the gates of water controlling regulators. A comparative picture of hydrological and ecological estimates of the study area for pre-project and post-project periods and after reestablishment of the optimum flood management option corresponding to the ecohydrograph has been computed. The flood management *ie* timing and regulation of water levels corresponding to the ecohydrograph is the option for decision making.

Hence an indicator-based relationship as a decision aid framework for ecohydrological consideration in flood management in deltaic floodplain has been developed.

1.3.2 Limitations of the study

The study area, a floodplain of the Gorai-Madhumati river system, is intervened with a flood control, drainage and irrigation project during 1981-83. Floodplain hydrological data are not available; in fact there is no practice of collecting floodplain hydrological data in Bangladesh. Floodplain hydrological data of the study area for this research have been generated using 2-D overland flow hydrodynamic model. Again there were no river cross-section data before 1992. Cross-section data of Madhumati River at 19 sections collected by the BWDB in 1992 have been used to develop bathymetry to generate overland flow for un-intervened *ie* pre-project period. During the period between 1981 and 1992 the river bed had undergone some changes which have been ignored as 1992 cross-section data have been used because of unavailability of river cross-section data around 1981. There were no measured water level data of Modhumati River downstream of the study area. There are measured river discharge data at Gorai Rail Bridge which is far upstream of the study area. Three-hourly long-term (1978-2007) average river water level data downstream of the study area (Station GORAI-197500) and three-hourly long-term (1978-2007) river discharge data upstream of but not far from the study area (Station GORAI-92800) have been used to generate overland flow for both post-project and pre-project periods. These are modelled data and were generated by the Institute of Water Modelling (IWM) using calibrated MIKE 11 hydrodynamic model. Modelled data have been used because measured data are not available.

A Digital Elevation Model (DEM) for the study area has been prepared from Irrigation Contour Map of 1967 of the BWDB with spot height intervals of 300 meters. Land elevation has been changed over the period of the last fifty years. Road and settlement elevation data are not available. Their elevations have been estimated from water level flood frequency analyses and checked through some sample survey elevation data collected from field survey. The DEM has been updated to digital terrain model (DTM) by incorporating estimated river bathymetry and road and settlement elevation data and old land elevation data.

Historical ecological data particularly fishery resources data of the floodplain are not available because of absence of data collection practices. Therefore key informant interview (KII) and focus group discussion (FGD) have been conducted over different groups of professionals of different ages to collect fishery and agricultural practices data.

Land-use change has been a continuous process. Flood management triggered land-use changes. At the same time development activities of other departments also enhanced the process. In this research only flood management intervention has been considered for land-use changes.

SOBEK 2-D overland hydrodynamic model developed by WL | Delft Hydraulics and MIKE hydrodynamic model of DHI have been used to simulate floodplain hydrology. Rainfall-runoff model of SOBEK cannot properly simulate floodplain hydrology and interaction between surface water and groundwater in case of highly modified rural areas of Bangladesh. Therefore base flow has not been estimated. Potential recharge has been calculated using empirical equations as provided in the Technical Report No 5 of the Master Plan Organisation (MPO, 1987). Rainfall collection stations are sparsely distributed in Bangladesh. Therefore Thiessen Polygon Rainfall Distribution method has been used to calculate rainfall. MIKE 11 NAM model has been used to generate rainfall-runoff for the study area.

1.4 Structure of the Thesis

This thesis consists of seven chapters. **Chapter 1**, this chapter, introduces the thesis with background and present state of the problem. It provides objective, specific aims and outcomes of the research. It also gives a brief method followed and tools and models used in analysing and generating data and assessing impacts and limitations of the study. **Chapter 2** gives an account of the review of literatures on linkage between ecology and surface water flow regime. It enumerates wetland, river and floodplain dependent ecological resources and describes the linkage between hydrological cycle and life cycle of aquatic plants and animals, ecological functions of floodplain, wetlands and rivers, flood pulse concepts, implication of flow alteration on aquatic habitat, impact of flood management measures on ecohydrology. It also justifies the need of such research on floodplain ecohydrology. **Chapter 3** describes how a relationship between ecology and hydrology, and a decision aid framework to find out hydrological need and optimum flood management intervention for sustenance of the ecosystem of the floodplain have been developed. **Chapter 4** introduces the study area in details that includes location, topography, demography, land-use, hydrological and ecological setting, and flooding characteristics of the study area. It also gives an account of data sources, data collection and data generation that include collection of historical land records, topographic field survey, assessment of land-use change, development of digital terrain model, generation of floodplain hydrological data and ecological data investigation. **Chapter 5** is devoted to land-use, hydrological and ecological data analyses and assessment of impacts on floodplain hydrology and ecosystem before intervention and because of flow alteration after intervention. It enumerates changes in land-use, floodplain functions, land type and fish habitat, fish production, and biodiversity. **Chapter 6** describes how the decision aid framework has been applied in the study area. It explains how a hydrograph and its corresponding flood management option suitable for maintenance of floodplain ecosystem has been developed through a trial and error process by regulating flood control structures and changing time and water levels of the canals connecting the river with the floodplain. It enumerates the improvement in hydrology and ecosystem if the optimum flood management option is introduced in the study area. It also suggests what changes in existing flood management interventions are to be made and what would be the operation rules for controlling flow structures. **Chapter 7** concludes the study and recommends areas of future research relating to floodplain ecohydrology.

Chapter 2

LITERATURE REVIEW ON LINKAGE BETWEEN ECOLOGY AND SURFACE WATER FLOW REGIME

2.1 Wetland and River Dependent Ecological Resources

Water is the most essential element of ecosystem, life formation and food production. Without water no ecosystem survives. Wetland and river are habitats of natural ecosystem and support most of the flora and fauna species. Ecological resources of most part of Bangladesh include birds, fish, frogs, snails, mollusc, tortoise, mongoose, snake, fox, etc and water lily, arum, cane, bamboo, wild vegetables, etc which provide various services to the people. Rivers, khals (channel and canal) and wetlands provide opportunities to a large section of the rural poor for their livelihood activities and supplementary food sources. The loss of ability of the rivers and wetlands to support the subsistence activities causes economic hardships to the eco-subsistent section of the people of the society.

The extensive network of rivers, khals and floodplain wetlands in Bangladesh provides a hospitable abode for rich open water fisheries. Khals link up floodplain wetlands and rivers providing suitable aquatic habitat for reproduction, migration, breeding and growth. A section of rural people is dependent on fishing from these natural water bodies for their livelihoods. Subsistence fishing is carried out by members of households for home consumption as well as for sale. Open water fisheries are a major source of protein supply for the rural people. Open water fisheries are self sustaining as long as the habitat is not disrupted by change in water regime. Frogs are farmer's friend, keep the environment pest free, increase crop yields, and restore ecology. Snails clean water and represent an indicator of more fish; loss of snail means loss of fish and loss of fish means loss of birds.

Bangladesh has extensive floodplain wetlands that harbour and support a wide range of aquatic plants and biodiversity. Wetland edible plants are harvested by rural poor people as a source of supplementary food. Wetland plants are also harvested for firewood, thatching, mat-making, livestock fodder and medicinal use. The wetland plants provide vital nutrients for open water fisheries (Chowdhury, 2009).

2.2 Linkage between Hydrological Cycle and Life Cycle of Aquatic Plants and Animals

Hydrological cycle determines the richness, diversity and productivity of aquatic plants and animals. From spawning, drifting, breeding to migration and feeding, *ie* from living to reproduction, hydrological cycle plays important role at every cycle of the life of aquatic plants and animals. Plants are more resilient than animals. Therefore breakage or modification in the hydrological cycle affects aquatic animals more compared to plants. Spill of river water and flooding from rainfall govern floodplain hydrology. Plants intercept and take rainwater. Some rainwater is stored in depressions, some infiltrate the soil and some flows over the surface to the nearby stream. The hydrologic process of a floodplain is shown in Figure 2.1.

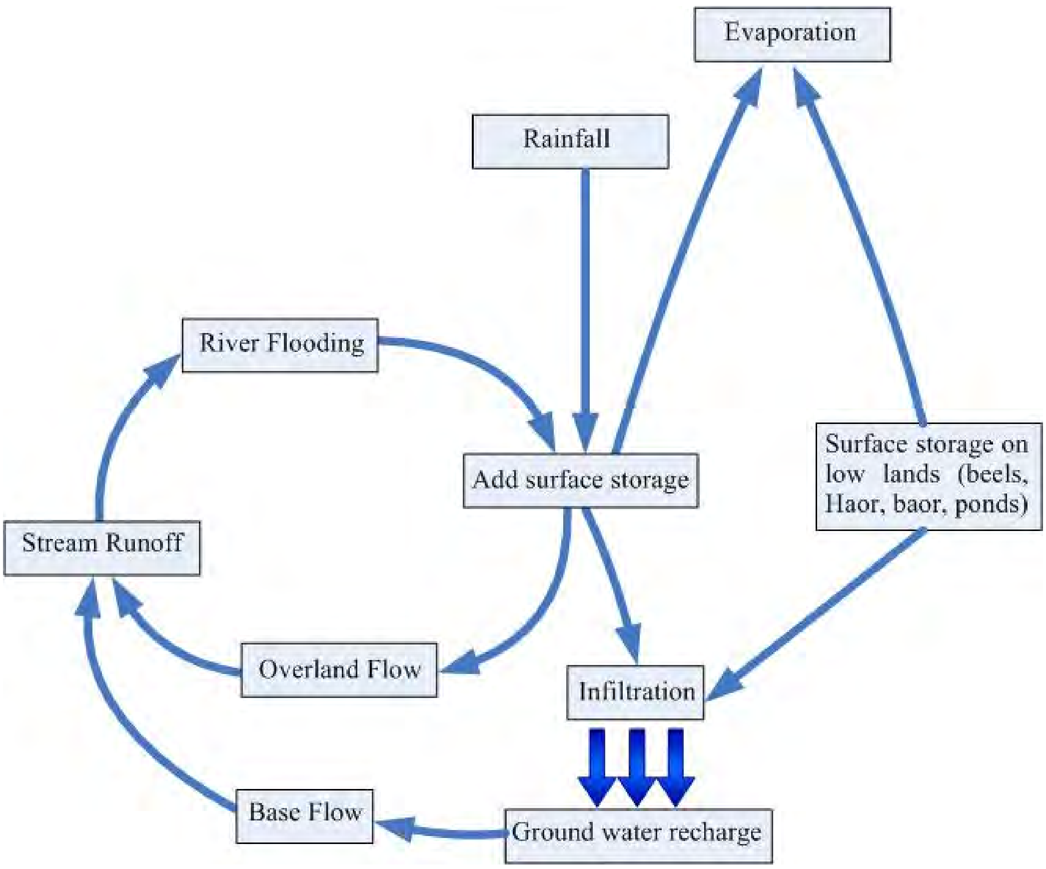

Figure 2.1 Flow movement in a floodplain (Source: Hassan, 2010)

The first rain in the early monsoon of February-March associated with thundershower agitates floodplain faunal community for mating and breeding. Without this natural event some fish do not lay egg. Rains in June rise water level of rivers and then river water enters into the floodplain with fish larvae/egg. During the monsoon aquatic animals live and grow in the floodplain. Then during recesion the adult fish migrate out to the river.

There are two principal seasons in Bangladesh, wet and dry, which define the available fish habitat at any given time. Fish species native to Bangladesh waters have evolved with and adapted to the hydrologic cycle. During the monsoon season (May through October) fish expand their range throughout the floodplain, while in the dry season fish seek refuge in discrete bodies of standing water. During each of the two seasons fish life cycles are quite different and are evolved to capitalise on habitat which has been created by hydrologic conditions (EGIS, 1997).

According to EGIS (1997) study, during the dry season, which is the most stressful time of the hydrologic cycle, fish are in maintenance or holding cycle in standing water. Except for a few small fish species, spawning and early rearing does not occur during the dry season. Recruitment of young fish into the population has already occurred, and dry season habitat can therefore be defined as maintenance habitat. The only life stage activity that defines maintenance habitat is rearing and holding.

2.3 Ecological Functions of Floodplain, Wetlands and Rivers

Junk *et al* (1989) define floodplain as "areas that are periodically inundated by the lateral overflow of rivers or lakes, and/or direct precipitation or groundwater; the resulting physicochemical environment causes the biota to respond by morphological, anatomical, physiological, phonological, and/or ethological adaptations, and produce characteristic community structures". They further state that this ecological definition recognises that flooding causes a perceptible impact on biota and that biota display a defined reaction to flooding.

A conceptual illustration of a floodplain with its aquatic, riparian, wetland and upland habitats and how they overlap (USEPA, 1989) is shown in Figure 2.2.

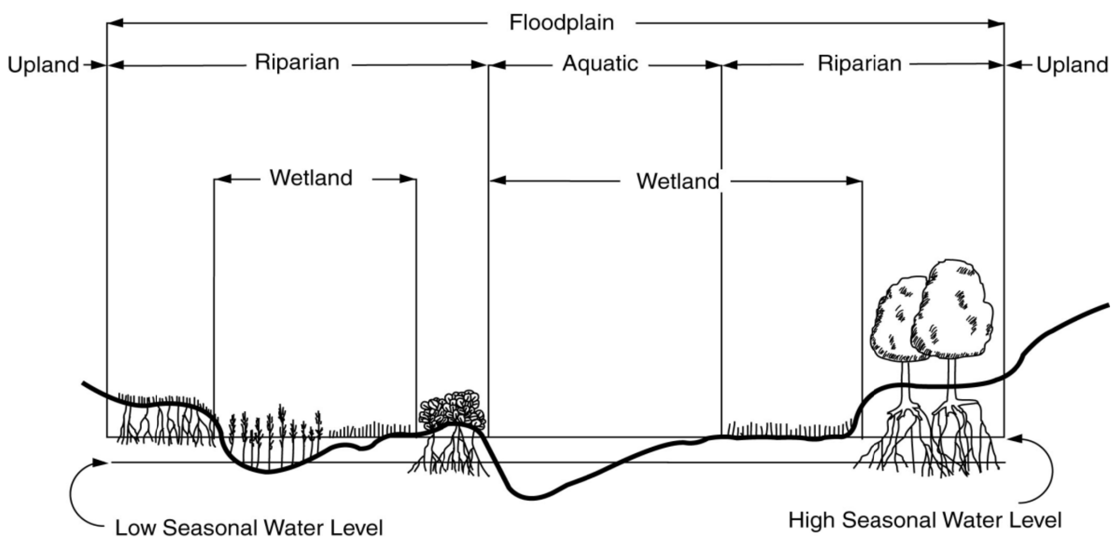

Figure 2.2 Floodplain habitats (Source: USEPA, 1989)

Floodplains support a range of valuable terrestrial and aquatic ecosystems. The margins of floodplains provide habitat for plant and animal communities specialised to take advantage of this land-water interface. Floodplains maintain plant and wildlife habitats. Its hydrologic and vegetation diversity provide important resting, feeding and nesting areas for many species. Aquatic and wetland areas provide habitat for fish. Inundated floodplains are important nursery and feeding areas of juvenile fish and other aquatic life.

Inland water bodies are source of freshwater upon which people and other biodiversity depend. Freshwater is essential for the functioning of many provisioning and regulating ecosystem services. Rivers provide water for production (irrigation, energy, fish) and domestic use (drinking and sanitation). Freshwater is essential for human well-being. In Bangladesh there are 790 rivers with 1,094 million acres feet of water (BRAC, 2008). Surface level freshwater is ample in Bangladesh as it is located at the confluence of the Jamuna (Brahmaputra), the Ganges, and the Meghna rivers.

Floodplain river systems are both highly valuable and highly vulnerable. Despite their high values, floodplain river habitats are now among the fastest disappearing of all ecological systems. The high values of floodplain river systems are due to their:

- high biological productivity (and high potential value of exploitable resources)
- high resilience to heavy exploitation levels and climate changes

- high biodiversity and
- multiple alternative livelihood opportunities.

Their high vulnerability is due to:

- the often conflicting demands of different sectors (*eg* fisheries, agriculture, transport, forestry, water abstraction, water drainage, housing, industry), and
- negative impacts from upstream sources (*eg* pollution, deforestation).

Wetlands are one of the most prevalent ecosystems in Bangladesh. According to the first Ramsar Convention, a wetland consists of ‘areas of marsh, fen, peatland, or wasteland, natural or artificial, permanent or topography, with water which is static or flowing, fresh, brackish or salt including areas of marine water’ (Ramsar Convention Bureau cited in BRAC, 2008). This includes rivers, streams, lakes, rice fields, shrimp farms, inland flooded forests, swamps and coastal mangroves. Wetlands offer numerous regulating services. Some of the provisioning services that can be found in wetlands are water (for rice cultivation and aquaculture), grazing land, food, fiber, and medicines. Regulating functions include providing nutrients through floods, natural purification of water, and recharging of groundwater (Ratner *et al*, 2004). Additionally, wetlands help to store flood water, stabilise shoreline, reduce soil erosion, remove or retain nutrients, and provide food for plants and animals. They offer water transportation, preserve biodiversity, and stabilise micro-climates (Billah, 2003). They are ecologically, economically, and culturally significant.

Healthy ecosystems carry out a diverse array of processes that provide both goods and services to humanity. Here, goods refer to items given monetary value in the marketplace, whereas the services from ecosystems are valued, but are rarely bought or sold. According to Ehrlich and Ehrlich (1991), Lubchenco *et al* (1993), and Richardson (1994), ecosystem process, goods and services are:

Ecosystem processes

- Maintenance of energy flux, dissipation, climate modulation
- Maintenance of hydrologic flux, hydrologic cycle, water quality
- Biological productivity, plant pollination

- Maintenance of biogeochemical cycling, storage, mineral-gaseous cycles, water-air quality
- Decomposition, weathering, soil development-stability, soil quality
- Maintenance of biological diversity
- Absorbing, buffering, diluting, detoxifying pollutants-xenobiotics

Ecosystem goods include food, construction materials, medicinal plants, wild genes for domestic plants and animals, and tourism and recreation. Ecosystem services requirements include maintaining hydrological cycles, regulating climate, cleansing water and air, maintaining the gaseous composition of the atmosphere, pollinating crops and other important plants, generating and maintaining soils, storing and cycling essential nutrients, absorbing and detoxifying pollutants, and providing beauty, inspiration, and recreation.

2.4 Flood Pulse Concept

The flood pulse concept (FPC) (Junk *et al*, 1989) describes the biological and biogeochemical processes in the river-floodplain system, which considers the lateral exchanges between the rivers and their floodplains as well exchanges between terrestrial and aquatic phases in the same floodplain. The floodplain area is termed as the “aquatic-terrestrial transition zone” (ATTZ) because it alternates between aquatic and terrestrial environments (Figure 2.3). Hydrologists consider the river and its floodplain as one unit—the river-floodplain system—since they are inseparable with respect to the water, sediment, and organic budgets.

The principal driving force responsible for existence, productivity, and interactions of major biota in river-floodplain system is the flood pulse (Junk *et al*, 1989). The flood pulse *ie* the pulsing of the river discharge is the major force controlling biota in river-floodplains. It identifies the predictable advance and retraction of water on the floodplain of a river system as the principal agent controlling the adaptations of most of the biota. Therefore, periodic flooding is not the disturbance—flood prevention is the disturbance. Flood pulse is postulated to enhance biological productivity and maintain diversity in the system. Floods/flood pulses are part of the function of the river system.

The floodplain production returns stepwise to the channel. Production of organic load in the stream is distributed during the year cycle and is connected with production in the floodplain. Floodplain absorbs harmful effects of floods. Common pulses increase fish production. High pulse helps disperse seeds in the floodplain. Low pulse helps dry part of the floodplain that is needed for the lifecycle of the biological community. The connectivity between river channel and its floodplain is essential because functions such as production, decomposition, and consumption are driven by the flood pulse (Grubaugh and Anderson, 1988; Sparks *et al*, 1990) and water fluctuation drives succession between the river and the floodplain (van der Valk, 1981; Finlayson *et al*, 1989; Niering, 1994; Middleton, 1999).

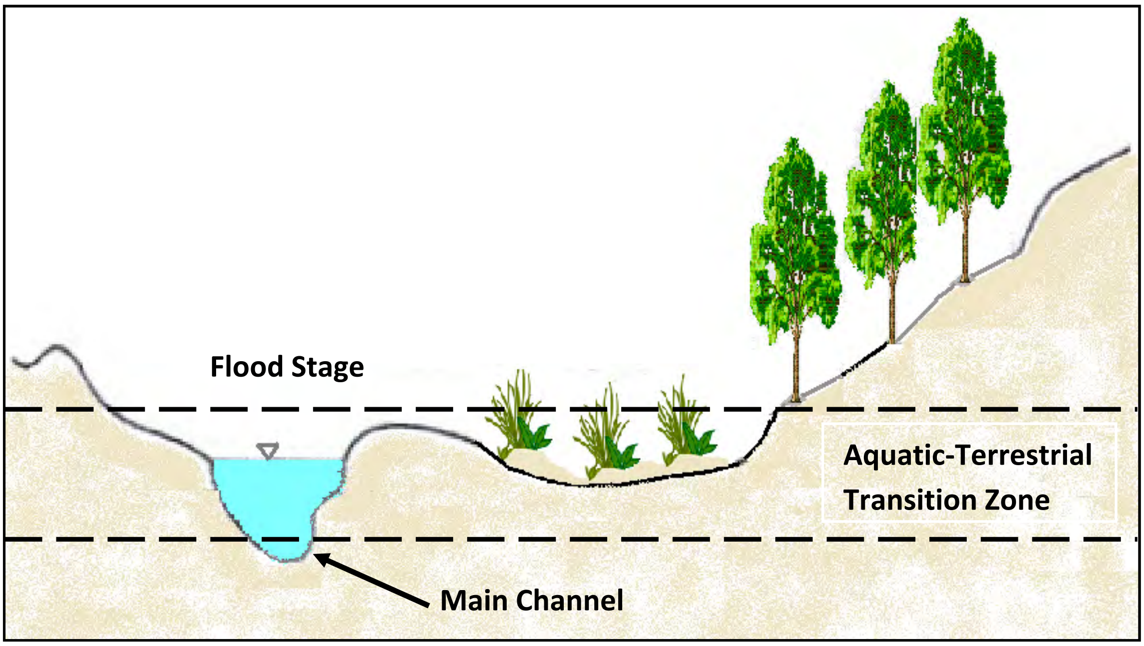

Figure 2.3 The aquatic-terrestrial transition zone

Large river-floodplain ecosystems have been severely altered throughout the world. One of the biggest perturbations to these ecosystems has been the suppression of the periodic flooding of river floodplain. Flood suppression is due to damming, leveeing and channelisation activities of humans. Flood suppression has effectively disconnected rivers from their floodplains (Bayley, 1995). The most important part of the aquatic phase of the hydrological cycle is at the productive "interface" of floodplain ecosystem which possesses great potential for adaptation of its biological structure and productivity to the intensity of flood pulses (Zalewski, 2006). de Graaf (2003a) has reported that annual catch varies with the extent of flooding, with high catches in wet years and low catches in dry years, which confirms the existence of a flood pulse. Conversely, if flood pulse is attained, fish yield increases. The reestablishment of flood pulsing in riverine and tidal systems is becoming recognised as an essential step in the restoration of wetlands worldwide (Middleton, 2002). Annual fish yields in the floodplains of Bangladesh appear to be maintained by the annual flood pulse, which provides nutrient rich environment needed for the fish survived in the floodplain (de Graaf, 2003b). The flood pulse paradigm is currently the most comprehensive and adequate approach to explaining and measuring ecosystem productivity of pulsed ecosystem (Lamberts, 2008).

The River Continuum Concept (RCC) (Vannote *et al*, 1980) introduces that a continuous gradient of physical conditions exists from headwater to mouth and physical conditions and biological components get continuous changes along the river channel. It states that headwater communities tend to optimise their use of allochthonous matter, whereas an organism living in the lower river reaches largely depends on the inefficiency of organisms living in the upper reaches to process organic material. The importation of dissolved and particulated organic material from the headwaters has little importance, due to a small amount and low quality in comparison with the organic material produced in the floodplain. The RCC fails to consider the biological significance of processes within the seasonal, aquatic habitats of floodplain (Junk *et al*, 1989).

2.5 Existing Flood Management Process

Floods in Bangladesh are classified as rainfall flood or local flood, river flood or monsoon flood, tidal or coastal flood and flash flood. Rainfall flood is caused by heavy monsoon rainfall within water management systems, which generate runoff volumes in excess of local drainage capacity, especially when rivers are at high stages. River flood is characterised by a relatively slow rise of river water levels, a long duration and a large area of inundation. This flood is related principally to the three major river systems in Bangladesh—the Brahmaputra, the Ganges and the Meghna. Tidal or coastal flood is resulted from tide surges associated with cyclonic storms and spring tides. And flash flood is a river flood that rises rapidly and has a short duration. It occurs as a result of intensive localised rainfall in the catchment area of a river high gradient.

The type of flooding determines the type of flood control system—FCD, FCDI or DR (drainage)—to be selected for implementation. A typical FCDI system is located in a floodplain. Prior to any human intervention these floodplains are subjected to seasonal flooding by the river. These floods are fairly well predictable and the cropping patterns practiced on the floodplains are adapted to the people. Most damaging are the less predictable flash flood during pre-monsoon period. The situation for a FCD system located in the coastal plains is not much different. Without intervention the area suffers from flooding during spring tides and on top of that during the dry season from salt intrusion. Consequently the yields are very low.

The aim of FCD/FCDI schemes has been "grow more food"; the environmental aspects of navigation, biodiversity and aquatic resources in FCD/FCDI schemes are in the list of trade off. Moreover, the knowledge gap and lack of data in relevant field has made it difficult to assess the negative impacts of the schemes on the environment and as such proper mitigation measures could not be adopted. Subsequently, the multi-sector approach in water resources development planning during eighties and nineties introduced initial environmental examination (IEE), environmental impact assessment (EIA), environmental mitigation plan (EMP), etc to make a scheme eco-friendly and these initiatives are practiced now-a-days in implementing/rehabilitating FCD/FCDI schemes (BWDB, 2006).

In a flood protection system, the embankment protects flood but obstructs the drainage of accumulated rainwater from within the flood protected area. To partly solve this drainage problem, regulator(s) in the embankment with flap gates on the riverside is constructed giving the area a FCD system.

2.5.1 Full control

In full controlled flooding systems flood control embankment is built along the whole bank of the river. Brahmaputra Right Embankment is a full control water management system. Embankment breach causes flooding inside the project and damages environment (WARPO, 1995a).

2.5.2 Controlled flooding

In controlled flooding systems structurally secure project is designed for full flood control but external flood waters are allowed for production of deepwater *aman*. Pabna Irrigation and Rural Development Project, Chalan Beel Polder B Project and Satla-Bagda Polder 1 Project are some of the controlled flooding systems (FCD/I) projects (WARPO, 1995a). Controlled flooding is an accepted drainage technique. It has been seen as a compromise between drainage and production of paddy that implies production losses (GOB, 2000)

2.5.3 Partial control and submersible embankment

In partial flood controlled systems structurally secure project is designed with submersible embankments to prevent river until May after which floodwaters overspill. In this case monsoon flooding remains unaffected. Shanghair Haor Project is an example of partial control system (WARPO, 1995a).

2.5.4 Tidal river management

Tidal river management (TRM) is an indigenous water and sediment management practiced by the local communities in the southwest coastal region of Bangladesh over generations. However the term TRM has been coined recently by the water management experts. The coastal rivers experience two cycles of tides every day. The high tide brings in water with huge sediment but cannot enter into the floodplain protected by embankment around it as a polder system of flood management in practice in the coastal region of Bangladesh. Then the sediment settles on the river bed and the bed goes up; but the land elevation inside the polder remains unchanged. The polder then suffers severe drainage congestions and water logging. As a solution to this problem, land elevation inside the polder needs to rise and the bed of the river to fall down. Dredging is not suitable in such a tidal environment. Tidal river management helps solve this problem. Tidal water, which carries huge sediment, is allowed, through cuts in suitable locations of the embankment, inside the polder in high tide. Silts deposit on the bed of the polder; land inside the polder continues to get elevated during this process; and clean water from within the polder during low tide flows to the river and the flowing water erodes the river bed and takes the sediment away from the bed of the river to the downstream. Thus a natural process of dredging the bed of the river and a land building inside the polder takes place simultaneously. This makes the polder free from water logging and keeps the river bed down and the river navigable. The TRM was planned and implemented in the southwest region of Bangladesh during 1997-2002 under Khulan-Jerssore Drainage Rehabilitation Project (BWDB, 2001) to relieve a huge area of Khulna and Jessore Districts from prolonged drainage congestion. The TRM reestablishes flood pulse in the floodplain and has been found acceptable to local community as an eco-friendly effective method to raise land, to remove water logging and to increase river navigability.

2.6 Implication of Flow Alteration on Aquatic Habitat

During the last half century, huge development interventions have been undertaken mainly for increasing food production for the increasing human population, improvement of road communication systems, industrialisations, urbanisations, etc. The major development interventions include the FCD/FCDI projects, construction of roads and highways across wetlands for easy and quick transportation, abstraction of ground water for irrigating agricultural crop fields, introduction and intensification of high yielding variety (HYV) of rice and mono cultivation of rice, indiscriminate use of insecticides, pesticides and chemical fertilisers in crop fields and the diversion of Ganges water flow (at Farakka, in India), etc, which have had profound impact on fisheries (BCAS and CDI, 2006). This bias towards agriculture has often had negative impact on capture fisheries; water bodies have been drained on an annual basis to irrigate rice; or flood control structures have been built to protect crops but have been acting as barriers to fish migration (WFC, 2007).

There has been water scarcity as a result of FCD/I embankments in the South-West area which have caused serious obstruction on fish migration for breeding and life cycle (WARPO, 1993). The species that require dwelling in different habitats for completion of their life cycle is greatly hampered due to non-fish friendly operation of the sluice gates in the FCD/I area. FAP 4 has identified excessive draining of *beel* water, river siltation and interference, with river water flow that had water deficiency contributing to declining the natural fish stock, catches and earnings. These have resulted in reduction of the traditional fisher number and in a switch to other occupation which affects the fisher's livelihood. Similar and more detailed information are available in FAP 17 study reports which elaborate that in flood control project the reduction of catch per unit area (CPUA) has been 81% annually (DFID, 2004).

Tsai and Ali (1997), observing Farakka Barrage, states that barrage, embankment and sedimentation are the three major factors causing the decreases in the habitat available for major carps. Over-fishing is the most important factor linked to decline the major carps in the inland open waters of the river system

2.7 Floodplain Modelling

Many study and researches have been conducted independently for floodplain modelling, flood hazard mapping, flood management and flood management impact assessment. Presently most of the floodplain modelling is mainly done with modelling software. The most common modelling packages are HEC-RAS by the Hydrologic Engineering Center of US Army Corps of Engineers (USACE), NAM model of DHI MIKE by the Danish Hydraulic Institute (DHI) and 1-D hydrodynamic, 2-D overland flow module of SOBEK-Rural by WL | Delft Hydraulics (WL | Delft Hydraulics, 2010).

HEC-RAS is a hydrodynamic model to perform one dimensional steady and unsteady river hydraulic calculation. It can be used with GIS, as shown in Figures 2.4 and 2.5, to create bathymetric surface of river in delineating the floodplain (USACE, 2009). It can also represent the floodplain inundation in GIS environment using TIN (Hatipoğlu *et al*, 2007).

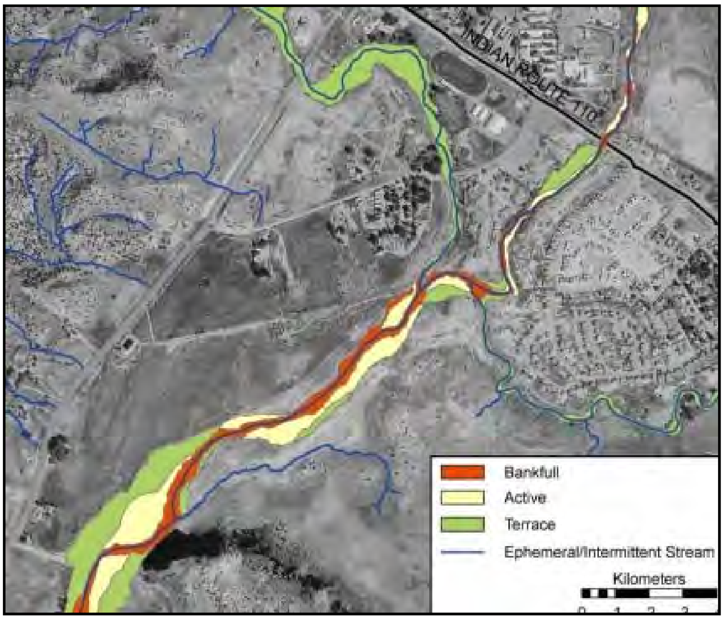

Figure 2.4 Floodplain delineation by HEC-RAS hydrologic model (USACE, 2009)

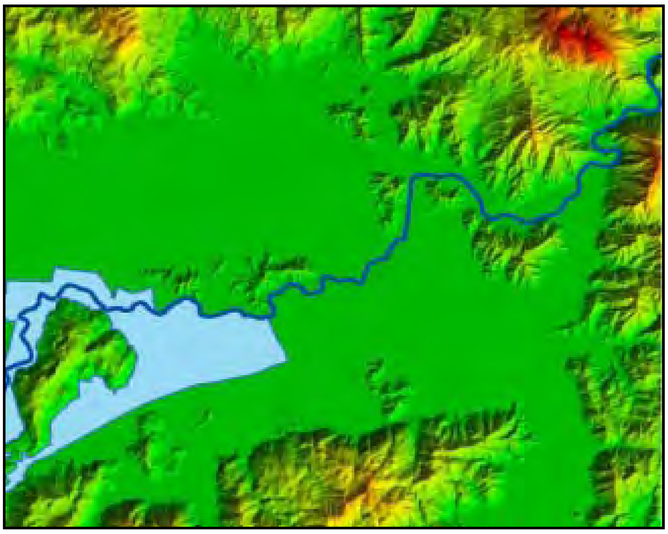

Figure 2.5 Floodplain delineation by HEC-RAS model (Hatipoğlu *et al*, 2007)

The NAM model is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in several different storages.

The MIKE 11 HD (hydrodynamic) model uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries and can describe both sub-critical and supercritical flow conditions through a numerical scheme which adapts according to the local flow conditions.

The 1-D and 2-D modules of SOBEK-Rural are implicitly coupled and solved simultaneously based on momentum balance and conservation of mass between separate computational layers while both layers use finite difference formula for volume and momentum equations based upon the staggered grid approach (Dhondia and Stelling, 2002). The flow in one dimension and two dimensions is described by two equations: the momentum equation and the continuity equation in SOBEK. Figure 2.6 shows a flood map generated from SOBEK.

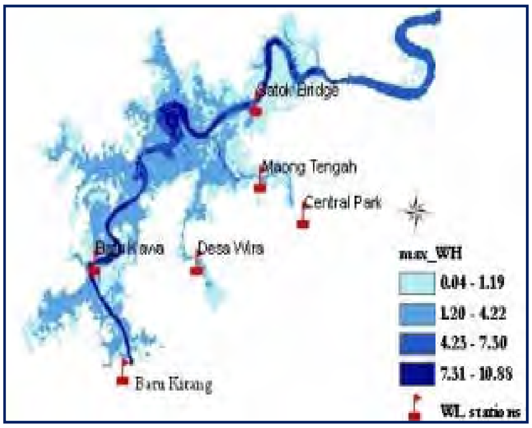

Figure 2.6 Flood map generated from SOBEK (Edna, 2007)

Another important part of floodplain modelling is the use of GIS techniques. It is also very important to maintain the quality of raster based modelling by using the proper resolution according to necessity. The outputs/results of floodplain model improve with the improvement of the raster resolution (Haile and Rientjes, 2005).

2.8 Research Needs

Ecosystem aspect in flood management has been compromised with more crop production. The knowledge gap and lack of data in relevant field has made it difficult to assess the negative impacts of flood management on environment and ecosystem, and as such proper mitigation measures could not be adopted. Subsequently, a multidisciplinary approach has been introduced for initial environmental examination (IEE), environmental impact assessment (EIA), environmental mitigation plan (EMP), etc to make water management schemes eco-friendly. This approach is in fact a multidisciplinary approach that examines the impacts of water management on the important biotic and abiotic components of the environment separately. Ecology and hydrology in a floodplain need to be examined from their relational perspective because they are naturally related to each other. The impacts of flow alteration on the ecological community of a floodplain should be seen from ecohydrological relationship point of view. Otherwise rehabilitation measures will not help reestablish the ecohydrological environment in the floodplain. Again flood pulse concept introduced by Junk e*t al* (1989) has been examined on unmodified temperate river-floodplain system. Efforts may be taken to reestablish flood pulse in a modified tropical deltaic river-floodplain system.

Chapter 3

DEVELOPMENT OF DECISION AID FRAMEWORK

3.1 Necessity for Indicator Based Framework

Naturally flowing floodplain rivers are among the more dynamic ecosystems on earth (Power *et al*, 1995), with enormous spatial and temporal complexity. River flows determine the distribution patterns of channels, back- swamps, marshes and tributaries that make up the floodplain (Ward, 1998). These floodplain wetlands also include freshwater and saline lakes, anabranches, lagoons, over flows, swamps and waterholes. The flow regime of a river, and its connections to floodplain wetlands, governs biotic responses, channel formation and sediment transfer (Junk *et al*, 1989; Walker *et al*, 2006). Flood management interventions have modified the hydrology of the floodplain and the ecosystem of the floodplain which depends on the flood flow and its natural variation. Performance of flood management projects is usually evaluated with respect to crop production and protection of the crop fields and homesteads. The impacts of flood management projects on the ecosystem of the floodplain have not been evaluated and therefore no rehabilitation for ecosystem improvement has been taken. Flood management projects have been rehabilitated only to improve the performance of the interventions *eg* embankment, regulator, etc. In fact indicator based impacts assessment of flood management project on floodplain hydrology alone or ecology and hydrology together is absent. It is necessary to consider ecohydrological criteria in flood management.

Hydrology plays important roles in regulating, connecting and regenerating water in, and sustaining environment and biodiversity of the floodplain and provides habitat, migration, production and conservation support to the ecological biota of the floodplain. Therefore an optimum arrangement between hydrological indicators such as water depth and flooded area, conveyance and duration of flow, recharge, and flood flow and extent of flooding and ecological indicators such as habitat area and depth, in-migration and out-migration, and biodiversity can be achieved that would help sustain the ecohydrology of a river-floodplain system. So an indicator based decision aid framework for consideration of ecohydrological criteria in flood management is necessary to find out optimum hydrological and ecological option that would help sustain floodplain ecosystem.

An indicator is a variable, which measures change in a phenomena or process (USAID, 2005). Indicator can be termed as a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor (DAC, 2002). A set of indicators has been identified, which are inter-related between hydrology and ecology of a river-floodplain system, to develop the indicator-based framework to find out ecohydrological response to various flood management options. This will help to develop appropriate guidelines and operation rules in introducing ecohydrological criteria in existing or future flood management projects.

3.1.1 Hydrological indicators

Hydrological indicators mainly refer to performance of the hydrological functions to meet up different functional capacities of the floodplain to regulate and store water and maintain connectivity between river and floodplain. Over the centuries, floodplains have been managing flood with natural features that provide floodwater storage and conveyance, reduce flood velocities and flood peak and finally drain the excess water. Floodplains allow surface water percolation and ultimately facilitate groundwater recharge. In addition, releasing monsoon water and providing it during the dry period is also an important function of the floodplain. Biological communities utilise floodplain habitats and their lifecycles are related to the flood pulse in terms of its annual timing, duration, and the rate of rise and fall (Junk *et al*, 1989). Table 3.1 shows the hydrological functions of floodplain along with indicators. Hydrological indicators have been worked out on the basis of some functions of the floodplain ecosystem. Indicators have been selected considering five important functions of hydrology to floodplain ecosystem. The functions are regulations of flow, connectivity of river with the floodplain, regeneration of water, environmental sustenance, and biodiversity habitat of floodplain. The regulatory function refers to the capacity of the floodplain to alleviate river floods during the monsoon season through storage of peak river discharge in the floodplain. During the dry season a main function of the floodplain is to retain and supply water. This relates to the capacity of the system to store water during the monsoon and to make this water, together with additional cross boundary river inflows and local rainfall, available during the dry period. Recharge is one of the important functions, which refills groundwater and surface water. One or more indicators have been worked out to represent a function, which are shown in Table 3.1.

Table 3.1 Hydrological functions and indicators

Functions	Indicators	Unit
Regulatory function	Maximum average depth in floodplain	m
	Flooded area	ha
Connectivity function	Conveyance characteristic (cross-section of the canal)	m^2
	Duration of flow in connecting river/channel with floodplain	day
Regeneration function	Recharge	Mm^3
Environmental sustenance	Maximum average flow (per unit width) in floodplain	$m^3/s/m$
Biodiversity habitat	Wetland area (*beel*)	ha

Assessment of the indicators of different hydrological functions requires specific methodology, tool and model. From both literature review and focus group discussions, hydrological indicators have been selected. All key informants and the participants of the focus group discussions wanted reestablishment of connectivity between Modhumati River and the study area. They need water for both agriculture and fish. Observed and modelled hydrological data have been used for the estimation of hydrological indicators.

Duration of flow in connecting river/channel with floodplain/wetland has been assessed based on daily water level. This indicator refers to the number of connecting days at specific point in the floodplain and has been assessed observing the water level value at the point. Conveyance characteristic of a channel with a floodplain is also an indication of connection capacity of the channel with the floodplain.

The storage (regeneration) function has three components: surface storage, soil storage and groundwater storage. Of these, groundwater storage and surface storage (flooded area) have been used as indicators. The area of the floodplain having depths of one meter or higher has been selected as flooded area.

Recharge has been estimated from the rainfall and the flooded area. Distribution of flooding recharge depends on soil texture and particle size. A study conducted by IWM in the southwest region has reported that particle size varies with elevation; particles are coarser in higher elevation and finer in lower elevation. Consequently, recharge from flooding gradually decreases from high to low areas. In this research, an additional 12.5% recharge has been taken as recharge from flooding following the study conducted by IWM (2006).

The environmental sustenance function refers to the maintenance of the quality of water and soil of the floodplain. It is achieved when a flood flow exists that helps exchanges of nutrient and organic matter and sediment/larvae/egg, in-migration and out-migration, mix and distribute nutrient and plant communities, agitate species mating, spawning and growing up, and transport bed-load and dispose waste between the river and the floodplain. Therefore flood flow must maintain a rational movement between the biotic and abiotic components of the habitat for environmental sustenance. To characterize the environmental function, two indicators have been developed for floodplain environment: maximum flow to maintain the floodplain environment, and wetland (*beel*) area as habitat to maintain the biodiversity of environment.

The values of these indicators have been determined for pre- and post-project periods and for ecohydrologically suitable option using various models and GIS techniques.

3.1.2 Ecological indicators

Ecological function of floodplain refers to the capacity of the floodplain to support the floral and faunal life for sustaining ecological services for socio-ecological development. Ecological functions of floodplain along with their indicators are shown in Table 3.2. Ecological functions and indicators have been worked out with respect to the hydrological functions and indicators of the floodplain. There are mainly four considerations upon which the indicators have been selected. The functions are floral and faunal habitats, migration support, biodiversity, and the production and productivity of floodplain. Extent of flood area during dry and wet seasons is vital for the floodplain flora including crops and the aquatic fauna especially fish and shrimp. Least amount of floodplain habitat is the pre-requisite for smoothing the ecological viability like regeneration and productivity of floodplain crops and fisheries. Average flooding area, depths variability, water flow condition and the seasonality of the connecting channels between floodplain and river are the main indicator for analysis of habitat condition in reference to specific floodplain crops and fishes. Migration support for the fish-fauna is prime important for their life cycle completion. Fish and other aquatic fauna have the high dependency on water flow for their spawning migration as well as lateral migration to spread over the floodplain searching for food. These processes are very important for production and productivity. Biodiversity of the floodplain and river is the basic component for ultimate sustainability. The more richness in biodiversity is the more strength of ecological sustainability. The numbers of species, and their evenness, dominances are the indicators of the floodplain biodiversity. The states of these indicators define the productivity and production of the floodplain habitats.

Table 3.2 Ecological functions and indicators

Function	Indicator	Duration	Unit
Fauna habitat maintenance	Flooded area (water depth>90 cm)		ha
	Maximum average depth	April to September	m
	Maximum average velocity	April to September	m/s
	Seasonality/connectivity	Annual	day
Fish migration support	Channel condition	April to September	length (km)
	Migration pattern (in and out, longitudinal/lateral)	April to September	month
	Spawning migration	April to September	month
	Hatchling migration	April to September	month
Biodiversity conservation	Species variation	Annual	Indicative species (number)
	Species dominance	Annual	Individual dominance
Fish production	Yield	Annual	MT

3.2 Development of Relationship between River-floodplain Ecology and Hydrology

Flood dynamics of river and floodplain make the floodplains rich with biological resources. The floodplain water regime, most importantly floodplain hydrology, nurtures and maintains ecological resources of the floodplain (Bunn and Arthington, 2002). In Bangladesh, early floods from rainfall during February-April stimulate the start of spawning of many floodplain resident species of fish. Heavy persistent rainfall in May connects floodplains and *beel* with adjacent rivers. From mid June the Brahmaputra River rises rapidly and causes rapid rise in the lower Padma River which in turn supplies flood waters to its distributaries in the South West region of Bangladesh. Till mid June channels usually drain water to the river from the floodplain. But this rise of floodwaters in the river cause a reversal flow to the channels and river floodwaters first enter into the floodplain. These river floodwaters carry spawn or hatchlings of fish, particularly major carps, and transport them by passive downstream drift on to floodplains between early June and July where they feed, grow and shelter from predators (WARPO, 1995a). In early September, water levels of rivers and floodplains start to fall and the rate of fall increases during October. A flood management project modifies the floodplain hydrology and the flow depth and variability of flood flow gets reduced.

Fish and other aquatic species use river, channel, canal, and floodplain as migration route, and spawning, breeding, hatchling, feeding and living ground as well. In a river-floodplain system many fish species migrate horizontally to the floodplain as part of their life cycle and stay for a good period of time in the floodplain before out-migrating to the river. Fish fauna that survived in the floodplain also spawn and breed at the onset of monsoon and they live in the floodplain. Floodplain flora including paddy also need water of different depths at different times over their lifecycle. Thus there is a relationship between the ecosystem of the floodplain and the hydrology on which the floodplain ecosystem is dependent upon. Some paddy flora can withstand certain maximum depth of water at a certain period of time of the year while some fish or other fauna cannot survive below a certain minimum depth of water at a certain period of time of the year. River-floodplain hydrology thus plays an important role in the life of the ecological community of the floodplain.

Fisheries population and the floodplain crops in Bangladesh are adapted to the variation of flooding and their life cycles are tuned to it. The majority of fresh water fish in Bangladesh breed during the monsoon months *ie* between May and August because of their dependency on seasonal floods, which inundate the floodplain essential for reproduction, feeding and living. Spawning patterns of some indicative fish are shown in Table 3.3.

Table 3.3 Spawning pattern of some fish species

Species	**Spawning Period**											
Rui (Labeo rohita)					━	━	━	━				
Ayer (Sperata aor)			━	━	━							
Catla (Catla catla)						━	━					
Shing (Heteropneustes fosilis)			━	━								
Ilish (Tenualosa ilisa)									━	━		
Common carp (Cyprinus carpio)					━	━	━					
Month	J	F	M	A	M	J	J	A	S	O	N	D

Most of the carp species (except Rui) in Bangladesh complete their spawning activity by middle of July, while Rui species require time up to August. On the other hand, fingerling out-migration may continue up to September (July to September). They initiate migration in April and complete in September. Catfish floodplain residents usually breed in pre-monsoon period of March-April while river species breed during May-June. Small indigenous species (SIS) are highly diversified in biological feature because number of species under this guild is high. Most of them are double breeder (per year).

Most of the carp fish prefer 0.5 to 1.0 meter of water depth where catfish's preference varies from 0.5 to 2.0 meter. On the other hand, SIS love comparatively low water depth (Boyd, 1982; Das, 1998 and WARPO, 1995a). Notably broadcast Aman (B. *Aman*), a deepwater floodplain paddy variety of Bangladesh, can tolerate 3 inches (0.076 m) of daily water level increase and up to maximum 3.5 m depth of water (Catling, 1992). A study conducted by the World Fish Centre (2007) has found that most of the floodplain fish species prefer 0.1 to 0.2 meter/second flow velocity, which is shown in Figure 3.1.

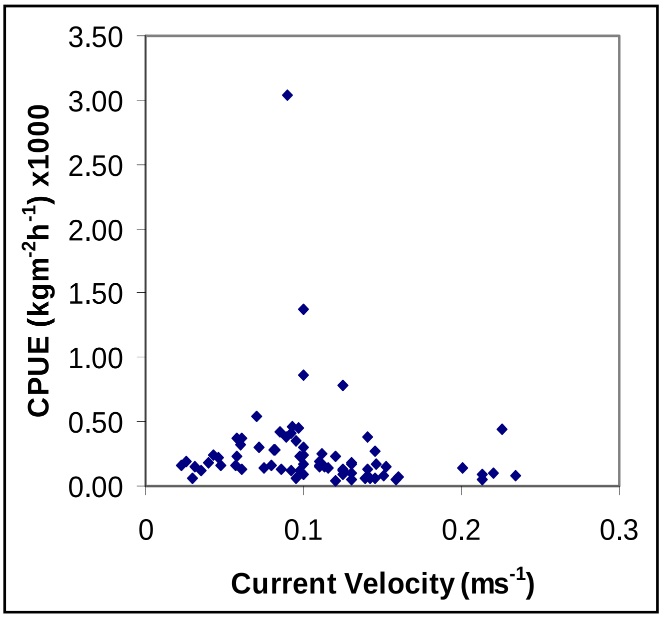

Figure 3.1 Flow velocity preferences of floodplain fish species (Source: WFC, 2007)

Thus a range of hydrological and ecological indicators suitable for ecological resources have been identified. Based on the water depth in the floodplain and seasonality, an indicator based relationship between hydrology and ecology has been developed for round the year from January to December comprising flood-cycle *ie* hydrograph, fish life-cycle and paddy crop-cycle in a floodplain. The relationship between floodplain ecology and hydrology in hydrographs is shown in Figure 3.2. Hydrographs at pre- and post-project periods *ie* before and after flood management interventions are also shown with other hydrographs. From this relationship a hydrograph which is suitable for floodplain fauna and flora ecosystem, hereinafter referred to as *ecohydrograph,* has been determined.

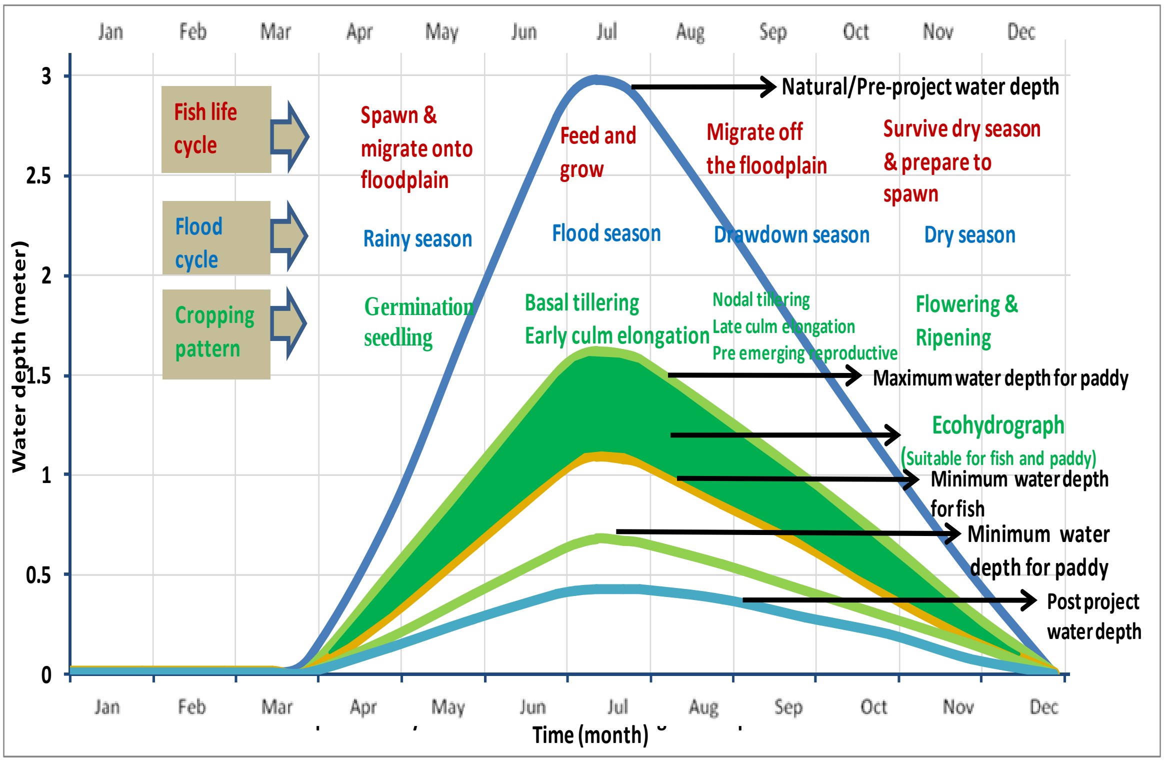

Figure 3.2 Relationships between floodplain ecology and hydrology in hydrographs

3.3 Formulation of Decision Aid Framework

A decision aid framework has been formulated to determine the ecohydrograph that will fulfill the need of floodplain ecological community, particularly different species/groups of fish and paddy. The components of the framework are a database and a model. The database comprises hydrological data and ecological data of the floodplain. The model is a hydrodynamic model that can simulate river and channel surface water using its one dimensional (1-D) hydrodynamic module and generate overland flood flow data of the floodplain using its two dimensional (2-D) hydrodynamic module. The framework is shown in Figure 3.3.

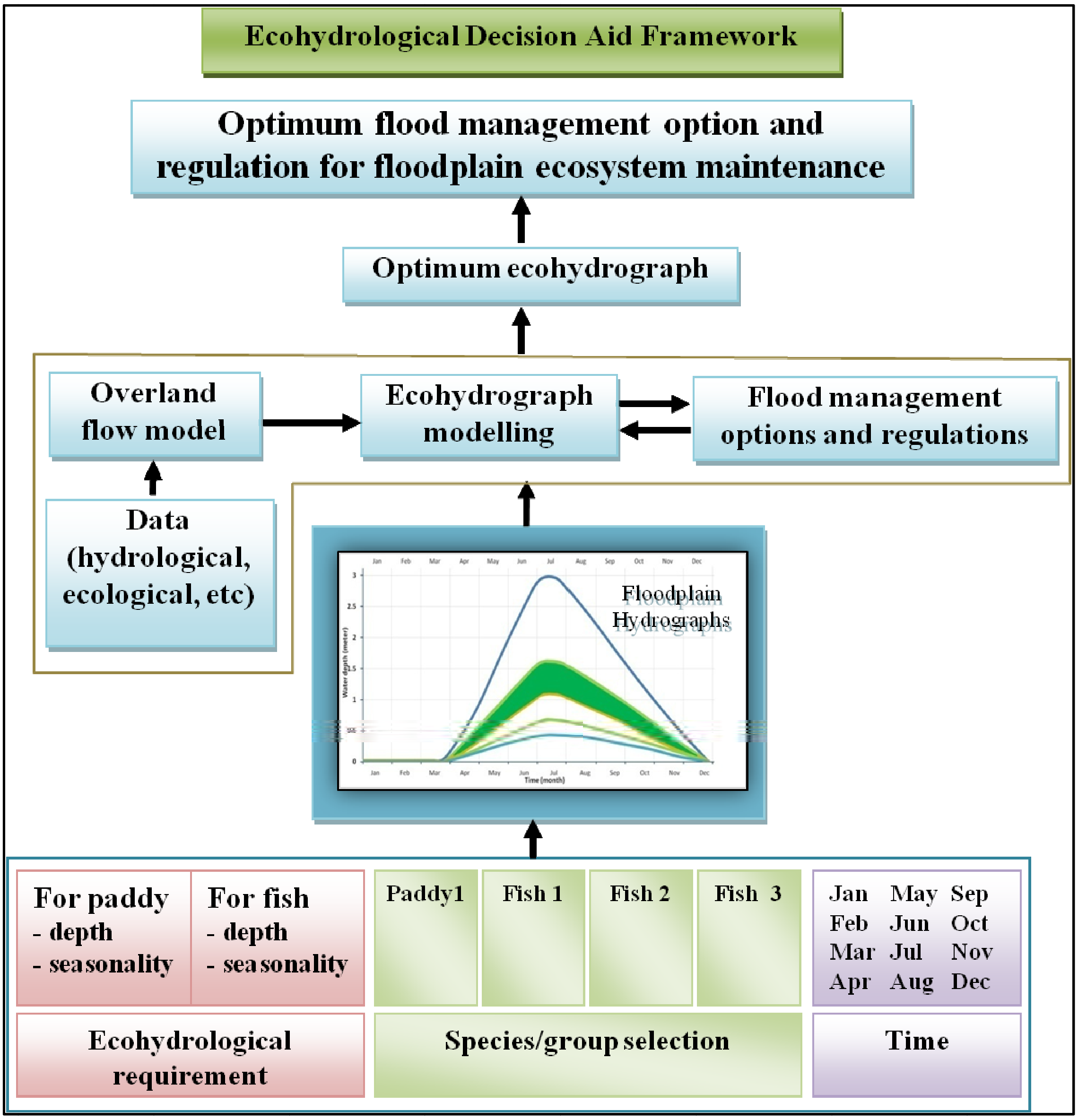

Figure 3.3 Floodplain ecohydrological decision aid framework

For different timing and water levels at the flood management regulators, various hydrographs have been generated from hydrodynamic modelling. From this trial and error process, an optimum hydrograph *ie* ecohydrograph, which is suitable for floodplain ecosystem, has been determined. The flood management option and operation rules corresponding to the ecohydrograph are the decisive optimum flood management option and operation rules for floodplain ecosystem maintenance.

3.3.1 Principles and strategies

The decision aid framework is constructed based on the relationship between hydrology and ecology of a river-floodplain system. A floodplain undergoes periodic flooding and drying and is a dynamic part of the river-floodplain system. The biotic community that resides in the floodplain is adapted to this dynamics. If there is a break or disturbance in the dynamics then the floodplain biota suffers many ways in their life-cycle. The variation of flow with respect to time determines the diversity and dominance of species. A modified floodplain can be made suitable for ecosystem by reestablishing the periodic flooding and drying, *ie* by introducing ecohydrograph, through governing flood flow. Because of the lack of floodplain hydrological data, overland flow hydrodynamic modelling has been made part of the decision aid to generate floodplain hydrographs. Through a trial and error process an optimum ecohydrograph and a flood management option that corroborates the ecohydrograph as a decision has been determined.

This decision aid framework is an input-output process and is made simple. River and floodplain hydrological data and floodplain topographic and ecological data are required as input. The hydrodynamic model generates floodplain hydrological data as output. The optimum output *ie* ecohydrograph and the corresponding flood management option including operation rules is the desired decision for flood management in a river-floodplain system.

3.3.2 Criteria and constraints

This decision aid framework is developed aiming at finding out a hydrological order which will be suitable for sustenance of the ecosystem of a river-floodplain system. It is applicable to a pulsed floodplain *ie* where an aqua-terrestrial transition zone between river and its floodplain exists.

If over-fishing or pollution degrades water and soil quality then application of ecohydrograph will not help much in sustaining the floodplain ecosystem. People’s acceptance of the eco-friendly flood management structures is also very crucial.

3.3.3 Procedure

A number of species or a group of species such as carp or catfish or small indigenous species (SIS) as fauna, and flora species such as a paddy species which is in much practice presently have been selected. Data on their range of hydrological requirement and seasonality have been collected. Using the hydrological data of the river and rainfall data of the nearest station of the study area as inputs to a hydrodynamic model, the floodplain hydrological data during the pre- and post-project periods have been generated. From these data a number of floodplain hydrographs have been constructed, which allowed determination of a common ranges of requirement for both flora and fauna *eg* fish and paddy. The hydrographs that fall within this common range are suitable for both fish and paddy. This common range hydrograph or hydrographs are the ecohydrographs. From ecohydrograph modelling, through a trial and error process with different timing and water levels at regulators, using 2-D overland flow model, the optimum ecohydrograph and its corresponding flood management option have been determined.

3.4 Prediction and Decision Making

Following the procedure as described in the previous section, an optimum hydrograph has been determined that fulfills the hydrological requirement of both fauna and flora of the floodplain. The timing and water levels at the flood management regulators corresponding to the ecohydrograph are the best option for decision because this option, if applied as a flood management option, will be suitable for the sustenance of the floodplain ecosystem. Operation rules for flow controlling structures have been developed to attain the ecohydrograph for ecosystem sustenance of the floodplain.

Chapter 4

STUDY AREA, DATA COLLECTION AND DATA GENERATION

4.1 Selection Criteria for Study Area

The research aims at developing a decision aid framework for consideration of ecohydrological criteria for flood management in deltaic floodplain. To test this framework it is required to select a study area which has been a deltaic river floodplain, prone to flooding, intervened with flood management project; and whose land-use has been changed and ecology and hydrology modified and ecological resources declined. A floodplain of the Gorai-Madhumati river system at Purulia-Char Bhatpara of Kashiani sub-district intervened with a flood control, drainage and irrigation (FCDI) project by the Bangladesh Water Development Board has been selected as the study area.

The study area is a deltaic floodplain and part of the floodplain of Madhumati river—a distributary of the Ganges River. It falls under the Agro-ecological Region of Low Ganges River Floodplain (Brammer *et al*, 1988). It is situated at the left bank of the Madhumati River and was connected (presently disconnected) with a channel namely Bhatiapara *khal*. It was subjected to periodic flooding from the river before the FCDI project was implemented during 1981-83.

About 30 years ago, the study area was brought under the FCDI project aiming at protecting crop from flooding. Over the years the land-use, hydrology and ecology of the area have been changed, flooding and wetland area reduced and ecological resources declined.

For the research hydrological, land-use, topographic, and ecological data are required. The river discharge, water level and rainfall data are available. Physical features of the study area intervened by the FCDI project, historical land-use data, agricultural practice and some fishery data are also available. Floodplain hydrological data have been generated using hydrodynamic model. For these data generation, topographic data of part of the study area have been collected using electronic total station equipment.

Social survey techniques have been followed to collect data on ecological resources, particularly fish.

4.2 Study Area

4.2.1 Location

The study area, shown in Figure 4.1, is situated in Kashiani sub-district of Gopalganj district and is part of the southern floodplain of the Ganges delta in the South-western region of Bangladesh.

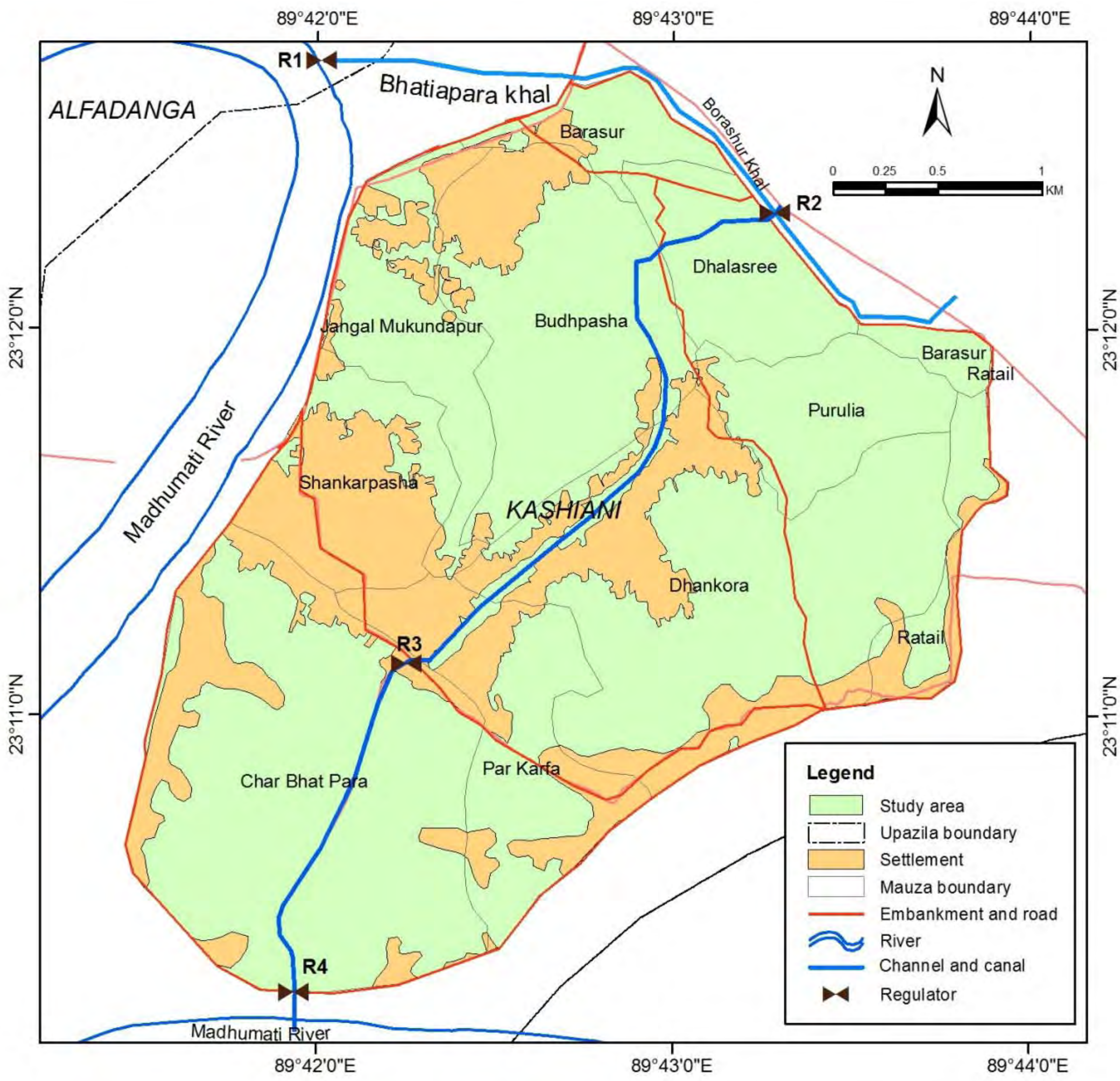

Figure 4.1 The study area

It is situated just at the left bank of Madhumati River between Bhatiapara and Shankarpasha road section. The total study area is about 11.42 sq km. The study area stands between the latitude of N $23^0 10'$ to N $23^0 12'$ and the longitude of E $89^0 41'$ to E $89^0 43'$. The study area comprises eleven Mauzas—lowest land revenue boundary with many plots of land—of two Unions under Kashiani Sub-district. The area of different Mouzas under the two Unions of Ratail and Kashiani are shown in Table 4.1.

Table 4.1 Area of Mauza within the study area under two Unions

Mauza name	Total area (ha)	Study area under each Mouza (ha)	Percentage of study area under each Mouza	Percentage of the study area
Barasur	471.37	43.53	9.23	3.81
Jangal Mukundapur	223.86	76.14	34.01	6.66
Budhpasha	149.31	149.31	100.00	13.07
Dhalsree	72.51	60.79	83.84	5.32
Ratail	290.84	32.82	11.29	2.87
Shankarpasha	157.80	78.67	49.85	6.89
Purulia	60.22	60.22	100.00	5.27
Dhankora	283.07	264.09	93.29	23.12
Char Bhat Para	539.45	268.63	49.80	23.51
Par Karfa	125.10	108.28	86.55	9.48
Total	2373.53	1142.47	48.13	100.00

Char Bhatpara, Dhankora and Budpasha Mauza cover about 60 percent of the study area. All these Muazas are part of the floodplain of the Madhumati River. Bhatiapara channel starts running from the Madhumati River towards east and enters into the study area at the north-western corner. Presently Bhatiapara channel is intercepted by the Bhatiapara-Shankarpasha road at the northern tip of the study area. Therefore water cannot flow between the Madhumati River and the floodplain of the study area. An internal canal, started from Bhatiapara channel at Dhalsree, runs through the study area and falls to Madhumati at Char Bhatpara, the southern bottom of the study area.

The study area is under the Flood Control and Drainage Irrigation (FCDI) project of Bangladesh Water Development Board (BWDB) constructed during 1981-83. The area is enclosed partially by road on the north-western border and rest by the FCDI project embankment.

4.2.2 Topography

The study area is mostly low lying. It has a general gradient from North to South. The elevation of the study area is mostly between 3 and 4 meters with respect to the Public Works Datum (PWD). About 50 percent of the study area is below 4 meters PWD. The area-elevation distribution estimated from the digital elevation model (DEM) is shown in Table 4.2 and Figure 4.2.

Table 4.2 Area-elevation distribution of the study area

Elevation (meter PWD)	Area(ha)	Area (%)
<0 m	18.64	1.63
0 m<elevation<1 m	3.68	0.33
1 m<elevation<2 m	17.52	1.53
2 m<elevation<3 m	117.2	10.26
3 m<elevation<4 m	419.48	36.72
4 m<elevation<5 m	220.84	19.34
5m <elevation<6 m	77.2	6.76
>6 m	267.84	23.45

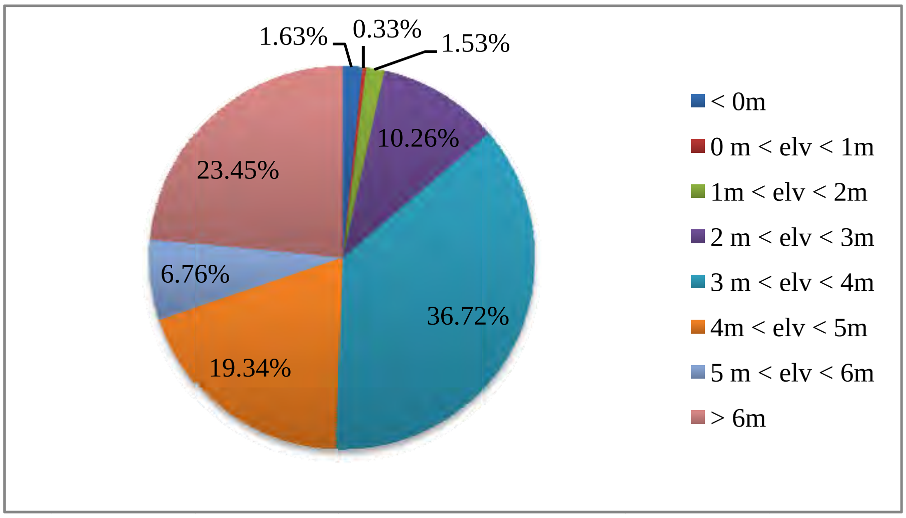

Figure 4.2 Area-elevation distribution of the study area

4.2.3 Demography

Demography is the statistical study of human population. The demography of the study area is similar to other parts of the country. Total population of the study area is 11,658 which comprise 48.5% male and 51.5% female population. About 1021 number of people live in a square kilometer of the study area. Male and female population under different age groups is given in Table 4.3.

Table 4.3 Male and female population under different age groups

	Age group population					
	0-4 year	5-9 year	10-17 year	18-34 year	35-59 year	>60 year
Male	749	855	985	1,442	1,125	495
Female	651	848	905	1,928	1,185	490
Total	1,400	1,703	1,890	3,370	2,310	985

(Source: Projected population in 2011 based on BBS Census 2001)

4.2.4 Land use

The current land use of the study area can be divided into four broad categories: agriculture, settlement, road, and water body. The current land use area of different types has been estimated using satellite image and GIS techniques. Road category covers kancha (made of soil), pacca (paved) and halot (narrow kancha road) roads. Water bodies are mainly of internal canal and pond. The study area has been estimated at about 1142 ha. Agricultural area covers about 798 ha, settlement area around 311 ha and internal canal and pond 11 ha. All types of kancha, pacca and halot cover about 22 ha of the study area. Different land uses are shown in Table 4.4 and Figure 4.3.

Table 4.4 Present land use area of the study area

Land Type		Area (ha)
Settlement		311
Agriculture		798
Water body		11
Road		22
	Total	1142

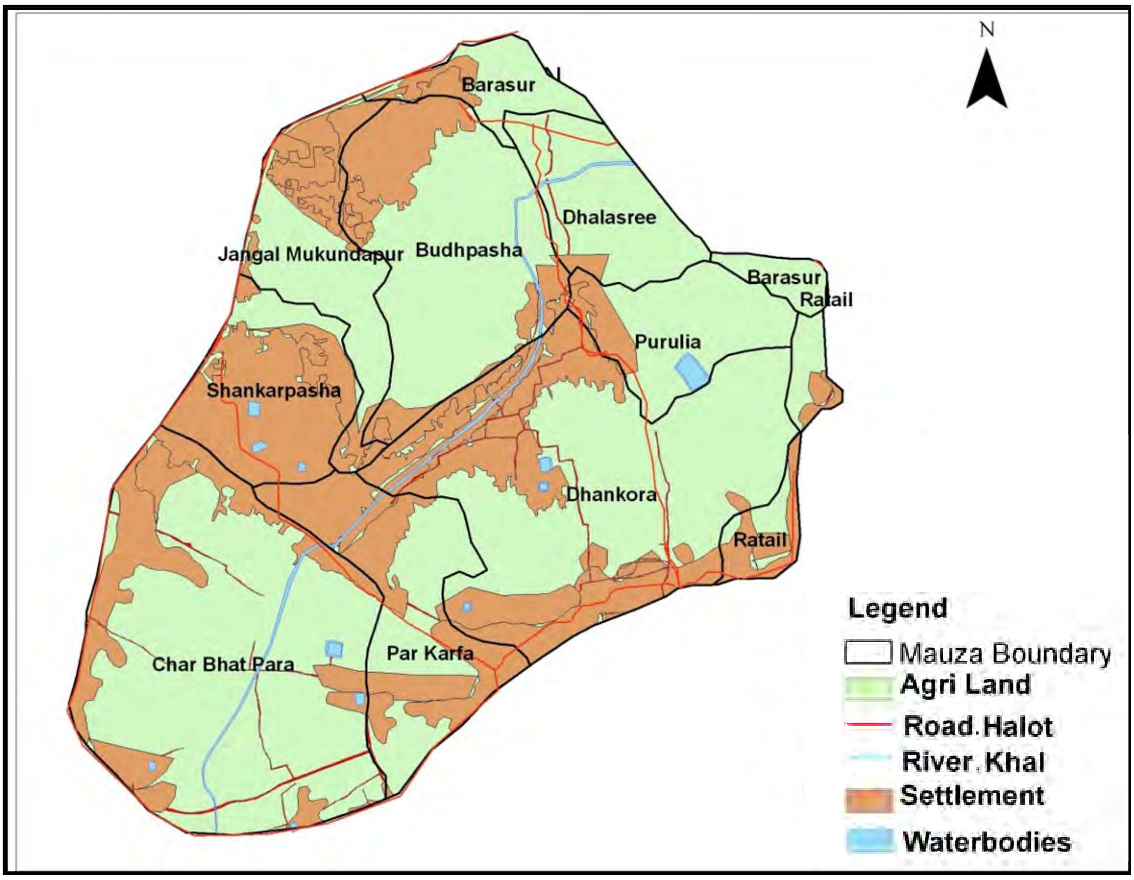

Figure 4.3 Present land use of the study area

4.2.5 Hydrological setting

The mean annual rainfall is 1831 mm, but 80% rain occurs during five months between June and October. During pre-monsoon period from March to June, generally 20% of the total rainfall occurs in the study area. There is no rainfall observation station in the study area. Rainfall values collected at three rainfall measuring stations located at Jessore, Madaripur and Faridpur have been used for the study.

The mean annual evaporation of the study area is 798 mm. The evaporation rate is found maximum between February and July and covers about 55 percent of the total mean yearly evaporation. The nearest evaporation station from the study area is at Faridpur (ID 62).

The study area is on the left bank of Madhumati River at Kashiani upazilla. Madhumati is the continuation of the Gorai River, a distributary of the Ganges River, and is flowing through southwestern region of Bangladesh and falls into the Bay of Bengal as the lower course known as the Baleshwar. The Kumar, the Nabaganga and the Chitra join with Madhumati through many channels in south of Mollahat Upazila. It passes through Magura, Narail, Bagerhat, Faridpur, and Gopalganj Districts. The course of this river is meandering and triggers bank erosion. It is relatively a narrow and shallow river as the average width of this river is about 500 meters and depth about 10 to 11 meters. Its flow has been reduced due to diversion of the Ganges waters at Farakka. From field observation and by checking water level record book, it has been found that Madhumati is a tidal river with two high and two low tides a day. The river has relatively clear water. The water quality is good from ecological aspects. Hatchling and migration of fish is still enough during June-July.

The Madhumati River dominates the hydrological characteristics in the area. Bhatiapara channel at the north-western part of the study area is closed; hence there is no flow in the channel even in monsoon. There is an internal canal in the study area. The off take of this canal is from the Bhatiapara khal at Dhalsree Mauza and the outfall at the Madhumati River at Charbhatpara (Figure 4.1).

Discharge data near Gorai Rail Bridge (Station ID SW99) and water level data at Bhatiapara (Station ID SW102) of the Madhumati River have been used for general hydrological analyses. These data have been obtained from National Water Resources Database (NWRD). Figure 4.4 shows the hydrograph of Madumati River at Gorai Rail Bridge Station and Figure 4.5 shows water level hydrograph at Bhatiapara Station.

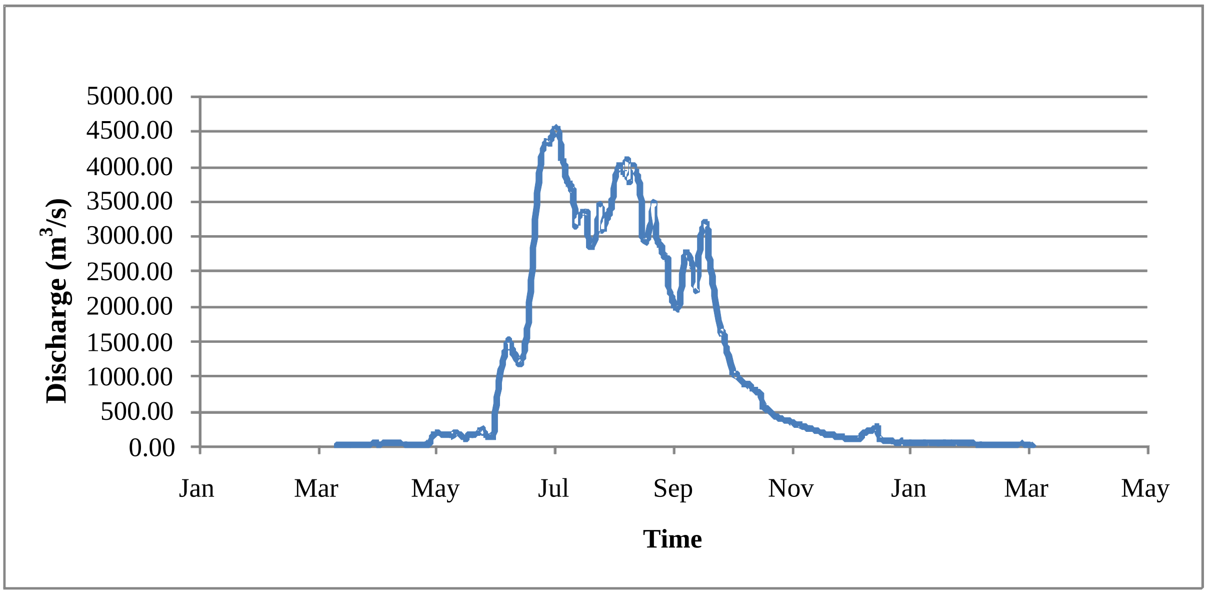

Figure 4.4 Hydrograph of Gorai-Madhumati River at Gorai Rail Bridge Station

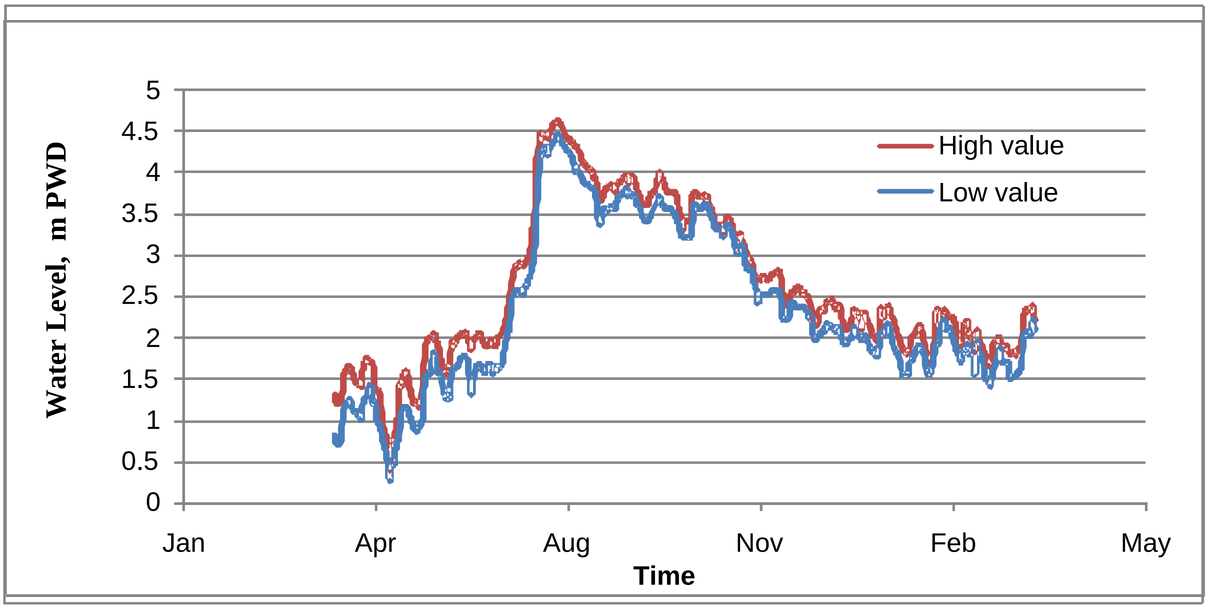

Figure 4.5 Water level hydrograph Madhumati River at Bhatiapara Station

The hydrology of the study area (Figure 4.1) has been modified because of the flood management project. Three regulators on the internal canal control the flow in the study area. One regulator is at the off take of the canal, north of the study area, at Dhalasree Mauza; one is at the border of Shankarpasha and Charbhatpara Mauza (middle) and the third one is at the outfall of the canal at Madhumati, the south bottom of the study area. The regulator at Dhalsree Mauza is out of service and the middle one is kept closed by the people of Char Bhatpara. There is a water level measuring gauge station of BWDB at Bhatipara Bazaar. Three-hourly water level data of Madhumati River are collected at this gauge location.

4.2.6 Ecological setting

Purulia-Char Bhatpara floodplain, situated in the Kashiani Upazila of Gopalganj District, is a complex ecosystem containing a cluster of water bodies including a channel connecting the Madhumati River system.

Fisheries resources of the study area are diversified with different fresh water fish habitats. Open water fish habitat of the study area includes river, channel, canal, beel and floodplain. Bhatiapara channel and Dholsree canal acted earlier as fish migration route to the study area. Out of 1142 ha of total study area, water body such as channel, canal and pond covers only 11 ha. After the FCDI project, the Bhatiapara channel has been closed and flooding reduced. Hence fish habitat and productivity have been decreased. Presently rainfall is the only source of water in the study area.

The study area and its surrounding have been endowed with vast water resources, fertile soil, and rich biodiversity. During the field survey, many people of different ages from 87 to 40 years have been interviewed and many senior people reported that the study area and its surrounding *beels* were home of many fish, edible plants and aquatic animals and plants. They stated that there were many birds, fish, frogs, snails, mollusc, tortoise, mongoose, snake, fox, water lily, arum, cane, bamboo, wild vegetables, etc in the area and these would provide livelihood support to them especially to the poor. They also reported that many of these resources had been depleted over time because of lack of water since the area was disconnected from the Madhumati River. Now only small indigenous species fish and catfish of small quantity are seen in the study area.

Broad-cast aman (*B. aman*), transplanted aman (*T. aman*), *boro*, sugarcane, jute, and vegetables are cultivated in the study area.

4.2.7 Flooding characteristics

Bangladesh is the biggest deltaic floodplain of the world. The whole country is regularly washed by rain or river floods. Local rainfall and floodwater carried by the rivers from outside the country cause flooding in Bangladesh and flooding is determined by rainfall and flood waters entering into Bangladesh from outside. The water level of the Madhumati River mostly determines the flooding of the study area. The water level of the Madhumati has been reduced because of water diversion at Farakka. Rise of water in Brahmaputra River in mid June causes rise in the lower Padma which in turn supplies flood waters to its distributaries in the south-west region of Bangladesh. The study area gets some flood waters from these distributaries. The rainfall determines the flooding in the study area. The level of water in the Madhumati River determines the timing of flood drawdown. In early September, water level start to fall and falling increases during October.

4.3 Data Source, Data Collection and Data Generation

Various data have been used for this study like historical land use data, topographic data, and various observed hydro-meteorological data such as water level, discharge, rainfall, evaporation, etc. Observed data have been obtained from different organisations like BWDB, WARPO, IWM, CEGIS, BMD. Some data such as fishery and topographic spot height have been collected from field survey and some have been generated using various models and tools. Data type, sources, acquisition and collection and model used for the research are given in Table 4.5.

Table 4.5 Models, data, source, data acquisition and collection for the research

Model used	Data collected	Source	Remarks
1D hydrodynamic model, ArcGIS 9.2, HEC-RAS 4.0	Discharge	IWM	Discharge data from:1978-2007
	Water Level	IWM, BWDB	Water level data from:1978-2007
	X-section	BWDB	Total 26 X-sections collected
2D Overland flow model, ArcGIS 9.2, HEC-RAS 4.0	1-D model results and Topographic data	Topographic field survey using total station equipment	2 sq km within the study area
		Contour map of BWDB 1967	Full study area
Land use map, ArcGIS 9.2	land use data	RS land record map from DLRS (21 maps)	Map prepared between 1941-1943
		BS land record map from DLRS (21 maps)	Map prepared between 1985-1987
		Satellite image from GoogleEarth	Image of 2007
Mike NAM model	Rainfall	BMD	Rainfall data from:1978-2009
	Evaporation	BMD	Evaporation data from:1989-2009
Recharge model	Rainfall	BMD	Recharge data from:1978-2009
	Land use	Geo-referenced land use map	
Ecological model	Fisheries Productivity	Field Survey (PRA, FGD, KII, Sampling), FRSS, Literature	Field survey during research period
	Fish Diversity/ Availability	Field Survey (PRA, FGD, KII, Sampling), literature	Field survey during research period
	Paddy, B. Aman	Literature and field survey (PRA, FGD, KII)	Field survey during research period

4.3.1 Historical land records

Land records comprise Mauza map and *khatian.* A Mauza map is a revenue boundary that contains plots of land and a khatian attributes the land use *ie* classes of land along with other information. These Mauza maps and khatians were prepared by the Directorate of Land Records and Surveys (DLRS) in the field following Cadastral Survey method. Each plot of land was physically surveyed in the field and the types of land such as pond, channel, river, wetland, lake, ditch, settlement, agricultural land, etc were recorded in the khatians. Therefore old land records contain the historical records of land use. Comparing historical land records of two different times, the changes in land use can be estimated. Historical land records, Mauza maps and Khatians, of 1941-43 (Revisional Survey-RS) and 1985-87 (Bangladesh Survey-BS) of the study area have been obtained from the DLRS. The BS and RS Mauza maps have been scanned and geo-referenced to convert it to GIS format. Then these geo-referenced Mauza sheets have been digitised according to the plots. The RS maps have been used to find out the land cover/land use of the study area before the intervention has been made *ie* before the project. Similarly the BS maps have been used to find out the land cover/land use after the intervention ie after the project. From these two sets of RS and BS land records, change in land use between pre-project and post-project has been estimated. Figure 4.6 shows the land use during 1941-43 while Figure 4.7 shows land use after 1985.

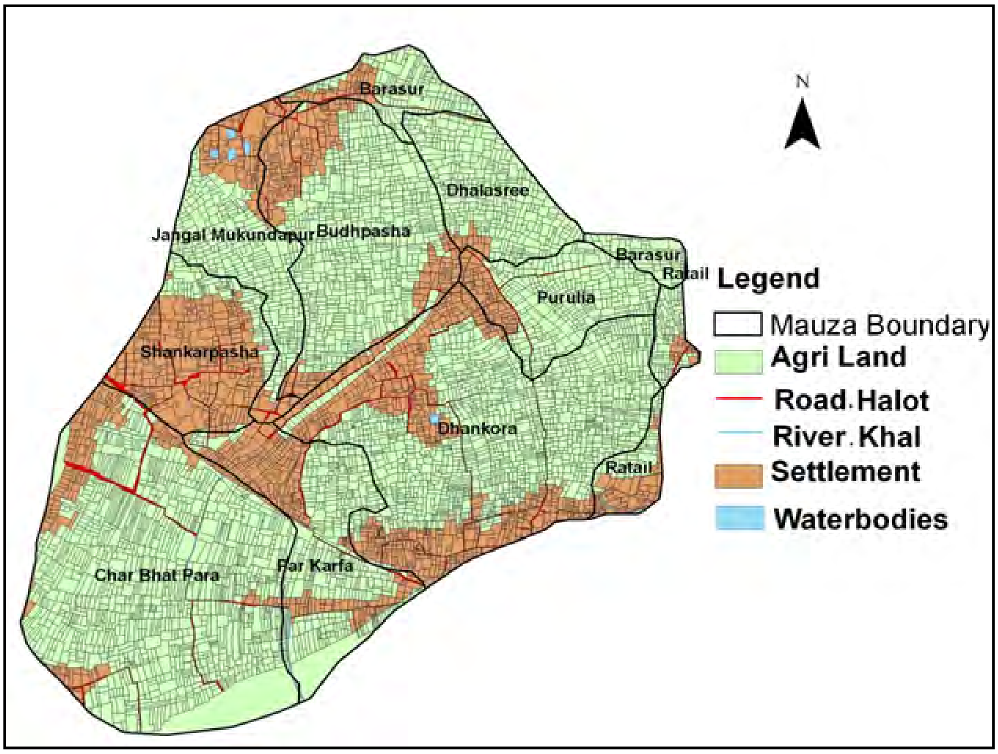

Figure 4.6 Land use of the study area during 1941-43 (RS map)

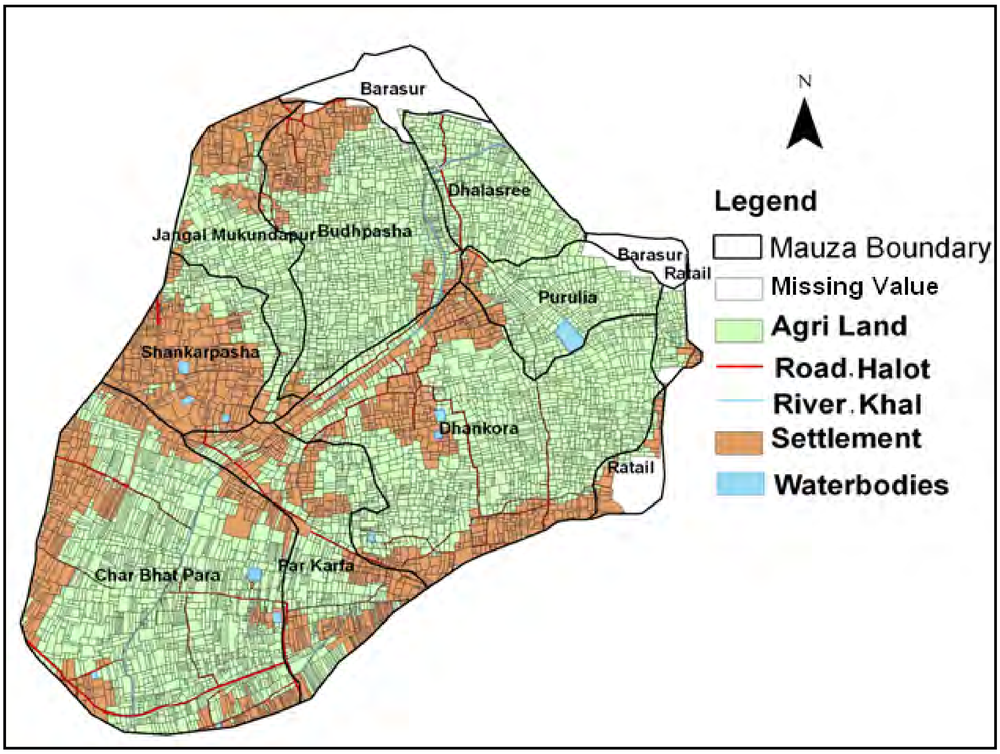

Figure 4.7 Land use of the study area during 1985-87 (BS map)

The land-uses have been estimated on four broad categories of land type *eg* settlement, road, agricultural land, and water body. Kancha road, pacca road, and halot have been represented as general road type and channel, canal and pond as water body type. Pre- and post-project land uses are given in Table 4.6.

Table 4.6 Land-use at post-project and pre-project periods

Land use	Unit	Post-project	Pre-Project
Settlement	ha	298	272
Agriculture	ha	816	850
Pond, canal, channel	ha	9	3.1
Road	ha	19	17
Total	ha	1142	1142

4.3.2 Topographic data

Topographic field survey

The topography of the study area is very low lying. Topographic data of the study area have been taken from the irrigation contour map (300 m) of 1967 of the study area. The contour map has been converted to point data to find the spot height of the study area.

A small portion of the study area, adjacent to the Madhumati River, has been surveyed very precisely. The main purpose of this field survey has been to make a precise topographic surface to find out floodplain inundation using 2-D overland flow model. The topographic field survey covers some portion of Shankarpasha, Jangalmukundupur and Budpasha mauzas. This survey has been conducted by the researcher using electronic total station equipment. Spot heights have been taken at an interval of 50 meters. Figure 4.8 shows the location of the spot heights of the surveyed area. Spot heights have been taken mainly on the agricultural land. Spot heights have also been taken on roads and internal canal to find out the alignment. Some settlement heights have been measured. The spot heights have been shown with other land use features in Figure 4.8 on a satellite image of February 2007 obtained from GoogleEarth. Some sample spot height data are attached in Appendix C.

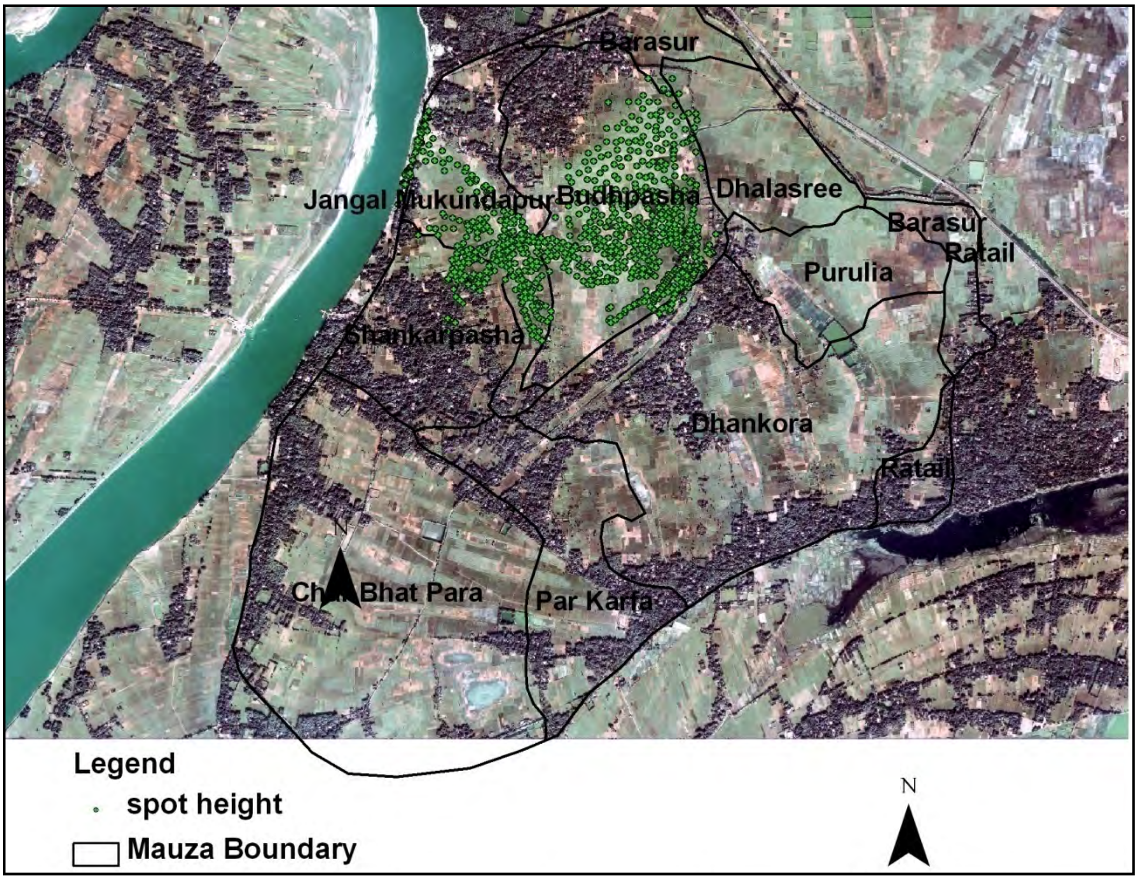

Figure 4.8 Spot heights taken in study area

Generation of river bathymetry

A bathymetric surface of the bed of a stretch of the Madhumati River has been generated to prepare a digital terrain model (DTM) needed for the overland flow modelling. Twenty-five cross sections of the Madhumati Rver available between Gorai Rail Bridge and Bardia have been used to generate river bathymetry as no bathymetry spot readings are available. HEC-RAS, HEC-GeoRAS and GIS techniques and tools have been used to generate river bathymetric surface.

Geometric data such as coordinates of streamline, cross sections, chainage have been entered into HEC-RAS. Then the cross section elevation, left bank, right bank, and channel chainage have been entered; and the cross section data have been interpolated at an interval 20 meters. All the cross sections have been geo-referenced according to streamline coordinate. The geo-referencing has been done based on Bangladesh Transverse Mercator (BTM) projection so as the streamline coordinates.

Geometric data have been imported from HECRAS, bathymetric grid created and merged with the topographic DEM and the geometric data have been extracted from the river basin TIN. Thus, 3D cross sections shape file containing topographic features has been generated. Interpolated cross-section, geo-referenced cross-section and bathymetric DEM of Madhumati River are shown in Figures 4.9, 4.10 and 4.11.

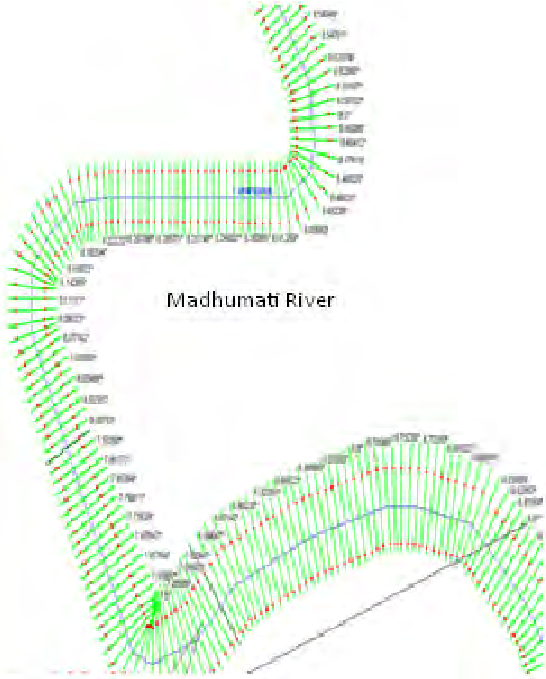

Figure 4.9 Interpolated X-section Figure 4.10 Geo-referenced X-section

Figure 4.11 Bathymetric DEM

Frequency analysis

A frequency analysis using Gumbel distribution method has been done with available water levels at six locations of the Madhumati River obtained from BWDB. From the frequency analysis 2-, 5-, 10-, 20-, 50- and 100-year return period water level data have been generated. Figure 4.12 and Table 4.7 show the generated water level of different return periods at 166 km, 173 km, 179 km, 182 km, 183 km and 191 km chainage stations.

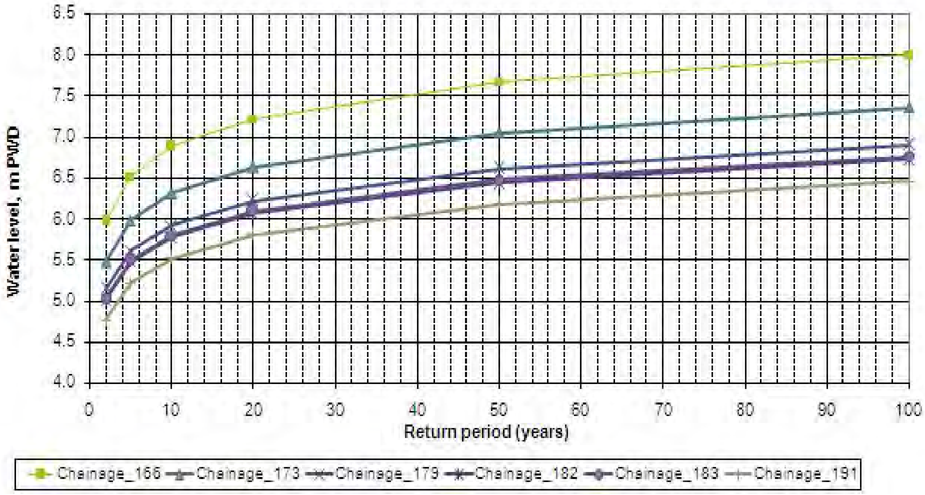

Figure 4.12 Water level of different stations with different return periods

Table 4.7 Water levels at different stations with different return period

Return Period T (year)	Chainage 166 km	Chainage 173 km	Chainage 179 km	Chainage 182 km	Chainage 183 km	Chainage 191 km
2	5.966 m	5.473 m	5.140 m	5.012 m	5.025 m	4.761 m
5	6.511 m	5.976 m	5.609 m	5.469 m	5.488 m	5.214 m
10	6.873 m	6.310 m	5.920 m	5.771 m	5.795 m	5.514 m
20	7.219 m	6.630 m	6.218 m	6.061 m	6.089 m	5.802 m
50	7.668 m	7.044 m	6.604 m	6.436 m	6.470 m	6.175 m
100	8.004 m	7.354 m	6.893 m	6.718 m	6.755 m	6.454 m

Figure 4.13 shows the flood surface of 100-year return period while Figure 4.14 shows the flood surface of 10-year return period. These water surfaces have been used to prepare the Digital Terrain Model (DTM) of the large area surrounding the study area

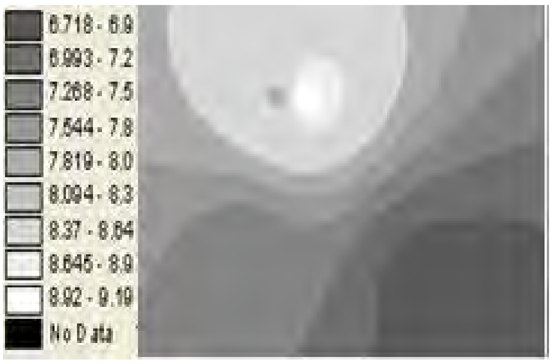

Figure 4.13 Flood surface of 100-yr return period

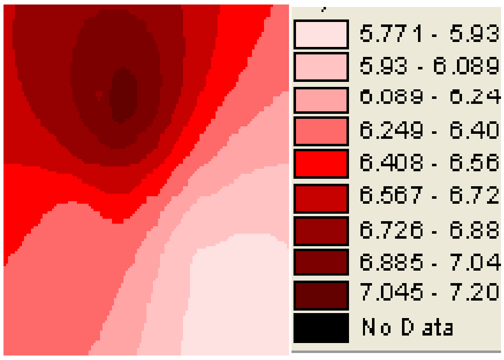

Figure 4.14 Flood surface of 10-yr return period

Development of digital terrain model

A DTM has been prepared for a large area of 137.5 sq km in and around the study area. Then the DTM has been updated for the study area on the basis of a topographic survey conducted by the researcher in a certain portion within the study area (Figure 4.8). At first the digital elevation model (DEM) of the study area has been prepared from the irrigation contour line data of 1967 of the study area.

From the irrigation contour line the spot height of the area has been prepared. Then by using the spot height the Digital Elevation Model has been prepared by using Inverse Distance Weighted (IDW) method in GIS. The current settlement, road and water bodies have been digitised from satellite image of 2007 obtained from GoogleEarth. The elevation of settlement, road and water bodies have been taken from the elevation surface generated from frequency analysis of various flood return periods of Madhumati River. The settlement elevation has been assumed as the height of the water level of 10-year return period. For the rural road the elevation has been assumed as the water level of 5-year return period and for the national road 20-year return period elevation has been taken. These return periods have been assumed by cross checking some sample spot height data of road and settlement collected during field survey using electronic total station. Figure 4.15 shows the spot height and Figure 4.16 the DEM of the large area.

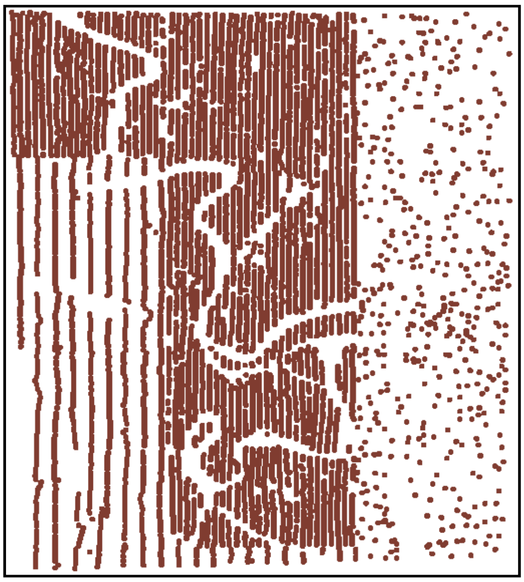

Figure 4.15 Spot height of the large area

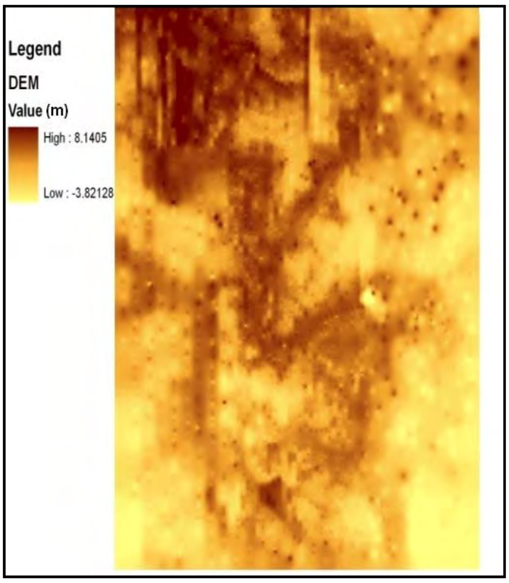

Figure 4.16 DEM of the large area

The DTM of the study area has been updated by using the spot height data collected from topographic survey. As mentioned previously some portion of Shankarpasha, Jangalmukundupur and Budpasha mauzas have been surveyed precisely and spot heights have been taken at an interval of 50 meter. These spot data have been used to update the topography of that portion in the DTM. Figure 4.17 shows the digital elevation of road, settlement and water body; Figure 4.18 shows the updated DTM of the large area including study area and Figure 4.19 shows the DTM of the study area.

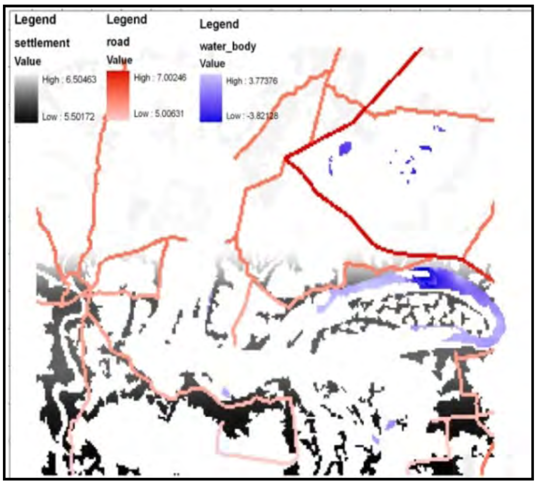

Figure 4.17 Digital elevation of roads, settlement and water bodies large

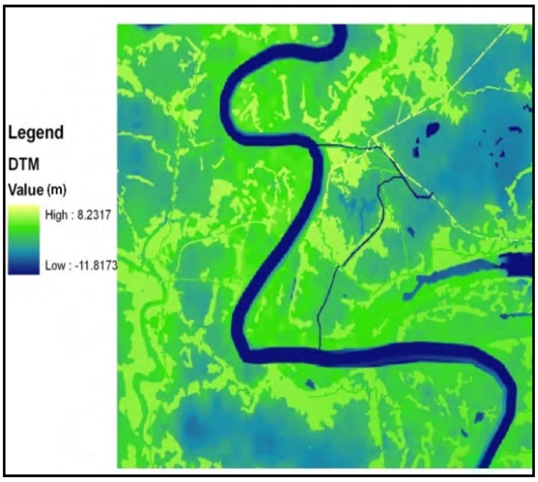

Figure 4.18 Digital terrain model of the surroundings of the study area

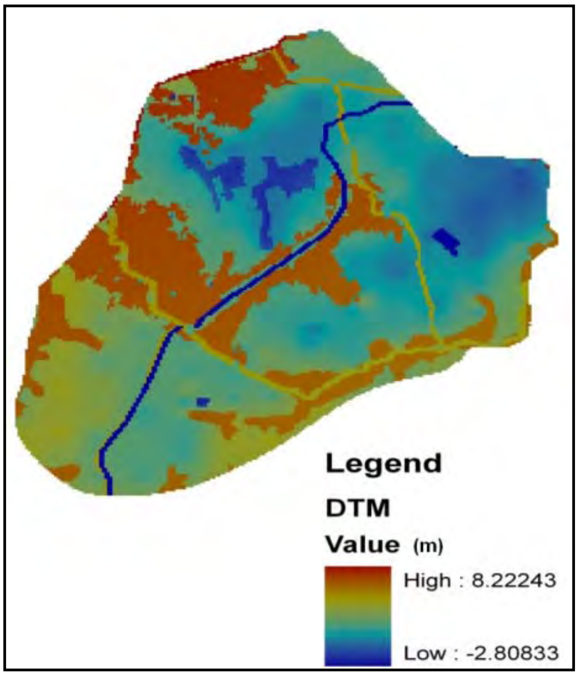

Figure 4.19 Digital Terrain Model of the study area

4.3.3 Hydro-meteorological data

Measured river discharge (Q) and water level (H) data of the Madhumati River have been obtained from BWDB and modelled data from IWM and their particulars are shown in Tables 4.8 and 4.9.

Table 4.8 Measured data of Madhumati River obtained from BWDB

Station Name	Station ID	Station Type	Data available
Gorai Railway Bridge	SW99	Q	1964-2006
Bhatiapara	SW102	H	1951-2009
Gorai Railway Bridge	SW99	H	1946-2010

Table 4.9 Modelled data of Madhumati River obtained from IWM

Station Name	Station Type	Data available
GORAI-92800	Q	1978-2007
GORAI-197500	H	1978-2007

Discharge and water level data of Madhumati River at 92800 m and 197500 m chainages have been obtained from Institute of Water Modelling (IWM). These are modelled data of the Madhumati River generated by the calibrated MIKE 11 hydrodynamic model.

After checking and initial analysis, modelled discharge and water level data obtained from IWM have been used for hydrodynamic modelling of the channel and the study area floodplain. Measured water level (H) data obtained from BWDB have been used for model calibration.

Water level and discharge data of Madhumati Rriver at different chainages, shown in Table 4.10, have been obtained from BWDB. The water level data have been used for frequency analysis to generate flood surface for different return periods.

Table 4.10 River ID and chainage

Year (1965-1990)			
Discharge (Q)		Water level (H)	
River ID	Chainage	River ID	Chainage
222	170.13	54	51
222	176.47	222	183.62
222	180.93	222	191.32
222	182.92	222	166.95
222	187.47	222	173.3
222	194.41	222	179.65
		222	182.21

Twenty-six cross-section data of Madhumati River between 1992 and 2002 have been obtained from BWDB and used to generate river bathymetry. Ground water observation data for three stations have been obtained from National Water Resources Database (NWRD) of WARPO and is given in Table 4.11.

Table 4.11 Ground water observation data obtained from WARPO

Station ID	Available Data
GOP 006	1978-2002
GOP 008	1978-2002
NAI 003	1978-2002

Meteorological data have been obtained from the Bangladesh Meteorological Department (BMD). Meteorological data mainly consist of rainfall and evaporation. Rainfall data have been obtained for three stations around the study area and are given in Table 4.12. The stations are Jessore, Faridpur, Madaripur and the IDs are 11407, 11505 and 11513 respectively. Rainfall data are available from 1977 to 2008. Evaporation data between 1989 and 1992 are available at Faridpur Station (ID 62).

Table 4.12 Meteorological data obtained from BMD

Station name	Station ID	Data Type	Available date
Jessore	11407	Rainfall	1977-2008
Faridpur	11505	Rainfall	1977-2008
Madaripur	11513	Rainfall	1977-2008
Faridpur	62	Evaporation	1989-1992

Discharge and water level data of the Madhumati River obtained from IWM and BWDB are attached in Annex A in the form of hydrograph. Rainfall and evaporation data obtained from the BMD are also given in Appendix A in the form of heightographs.

4.3.4 Generation of deltaic floodplain hydrological data

Flowchart for floodplain hydrological data generation

The generated digital terrain model (DTM) has been taken as the input for the 2-D overland flow modelling of the floodplain. Connectivity between river and floodplain needs to be established for generation of floodplain hydrologic data by modelling. Hydrological data for channel and canal (*khal*) that connect the river with the floodplain have been generated through SOBEK 1-D hydrodynamic modelling. A framework for generation of floodplain hydrologic data is shown in Figure 4.20.

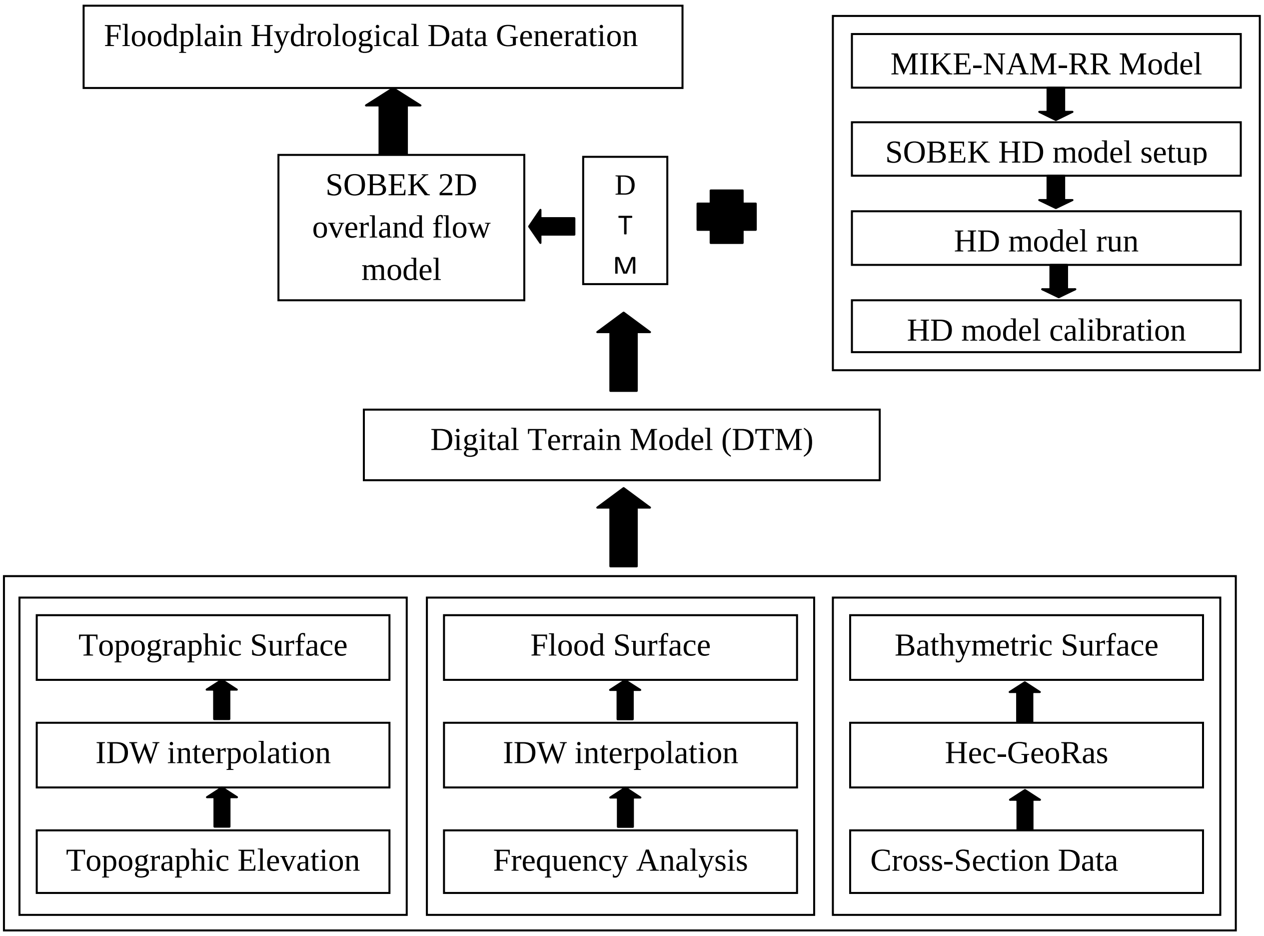

Figure 4.20 Flowchart for generation of floodplain hydrological data

Application of 1-D hydrodynamic model

One dimensional (1-D) hydrodynamic flow module of SOBEK model has been used to generate river and channel flows to the study area. The one dimensional flow has been described by two equations: the momentum equation and the continuity equation. The continuity equation reads:

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \qquad \text{4.1}$$

where, A_f = wetted area, q_{lat} =lateral discharge per unit length [m^2/s], Q = discharge [m^3/s], t = time [s], and x = distance [m]

The momentum equation reads:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + g \cdot A_f \cdot \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 RA_f} - W_f \frac{\tau_{wi}}{\rho_w} = 0 \qquad \text{.................................4.2}$$

where, the first term describes the inertia; the second term describes the convection; the third term describes the water level gradient; the fourth term describes the bed friction; and the fifth term describes the wind friction. Here Q = discharge [m^3/s], t = time [s], x = distance [m], A_f = wetted area [m^2], g = gravitational acceleration [m/s^2] (=9.81), h = water level [m] (with respect to the reference level), C = Chézy coefficient [$m^{1/2}/s$], R = hydraulic radius [m], W_f = flow width [m], τ_{wi} = wind shear stress [N/m^2], and ρ_w = water density [kg/m^3] (= 1000)

In hydrodynamic model settings, the following data have been defined:

- The simulation period and the computational time step
- Initial data and restart data
- Output options including parameters like water level, discharge, velocity, etc and time interval for output.

The model has been run with long-term average boundary condition of discharge at upstream and water level at downstream and the computational time step has been chosen as 3 hours. For the output option, water level and water depth have been selected and the output time interval has been selected as 3 hours.

For the purpose of modelling the river for the study area, the whole river system has been schematised in SOBEK model. During schematisation, data related to cross section, flow boundary, friction, etc have been given as input. Figure 4.21 shows the complete river system and the river in schematised form.

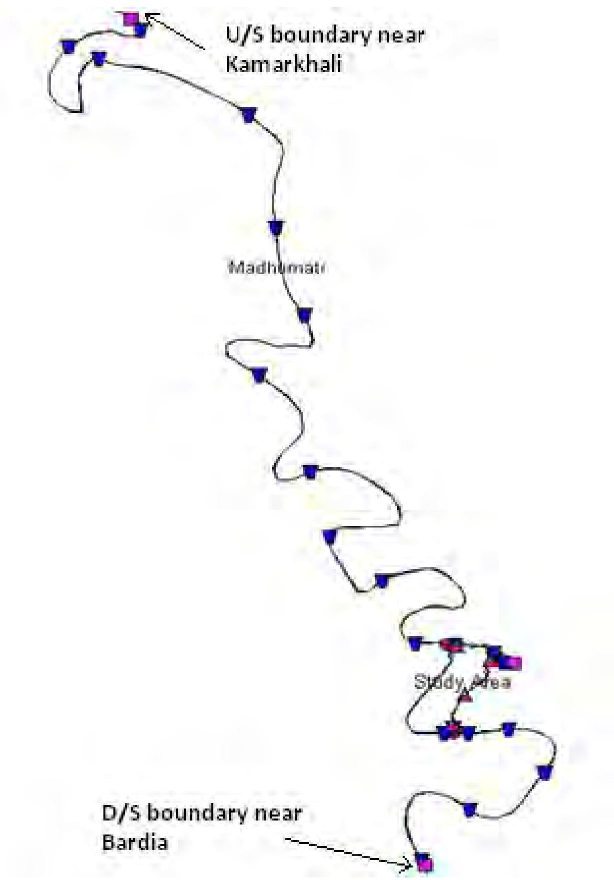

Figure 4.21 Schematisation of river network in SOBEK

Three boundary nodes have been used in SOBEK. The upstream boundary is placed at upstream of Madhumati River (Chainage: 928200) near Kamarkhali. Two downstream boundaries are placed—one at downstream of Madhumati River (Chainage: 197500) at Bardia and the other at *beel* Pabania at downstream of Bhatiapara channel that passes through the study area and falls into the Madhumati River again. Discharge data are used as upstream boundary and water level data as downstream boundary. SOBEK hydrodynamic model has been calibrated for water levels at Bhatiapara Bazar Station (Station ID Bhatipara 102) for monsoon period because water from river enters into the floodplain during monsoon period when water level is high in the river. This gives better simulation of overland flow in the study-area-floodplain. Figure 4.22 shows SOBEK 1-D hydrodynamic model calibration for the Madhumati River at Bhatiapara Station. The output of 1-D hydrodynamic model of the river and canal network has been used to simulate the overland flow model in the floodplain.

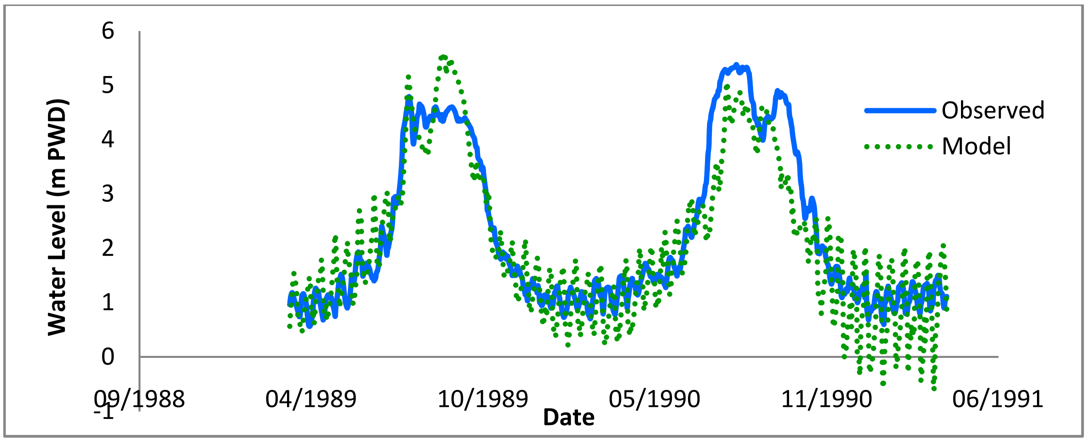

Figure 4.22 SOBEK model calibration for Madhumati River

Application of 2-D overland flow model

The 2-D overland flow module of SOBEK model has been used for simulating two dimensional overland flows in the study area. The two dimensional flow has been described by three equations: the continuity equation, the momentum equation for the x-direction and the momentum equation for the y-direction. The continuity equation reads:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \quad \text{...4.3}$$

where:

u	velocity in x-direction (m/s)
v	velocity in y-direction (m/s)
V	velocity: $V = \sqrt{u^2 + v^2}$
ζ	water level above plane of reference (m)
h	total water depth: ζ+d (m)
d	depth below plane of reference (m)

The momentum equations read:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{u|V|}{C^2 h} + au|u| = 0 \quad \text{.................................4.4}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + g\frac{v|V|}{C^2 h} + av|v| = 0 \quad \text{.................................4.5}$$

where:

u	velocity in x-direction (m/s)
v	velocity in y-direction (m/s)
V	velocity: $V = \sqrt{u^2 + v^2}$
ζ	water level above plane of reference (m)
C	Chezy coefficient ($\sqrt{}$m/s)
d	depth below plane of reference (m)
h	total water depth: ζ+d (m)
a	wall friction coefficient (1/m)

The momentum equations consist of acceleration terms, the horizontal pressure gradient terms, advective terms, bottom friction terms and wall friction terms. These equations are non-linear and they are a subset of the well-known shallow water equations that describe water motion for which vertical accelerations are small compared to horizontal accelerations.

The elevation reference values as in DTM have been taken as the land height. The time step has been taken as 1 day for GIS output. The output parameters are: water depth, velocity and discharge in both directions. The friction factor *ie* roughness of the floodplain has been taken as 0.03. The output hydrograph at each calculation node generated through 1-D Flow module for the connecting channel and canal has been used as the boundary data for the overland flow module. The 2-D model set-up is shown in Figure 4.23.

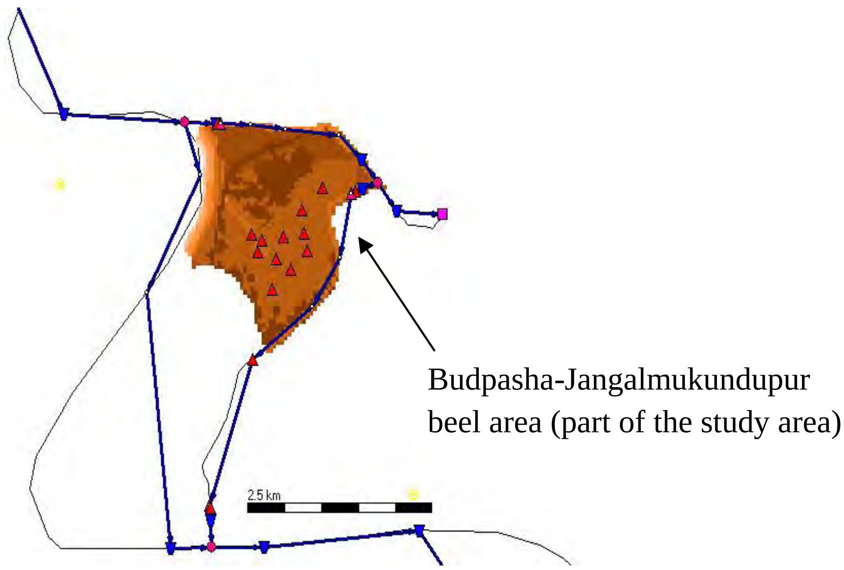

Figure 4.23 SOBEK 2D overland flow model setup

Generation of floodplain hydraulic data for the pre-project period

SOBEK 1-D hydrodynamic model has been used to generate flood flow data in the Bhatiapara channel and internal canals while SOBEK 2-D overland flow model has been run to generate flooding data in the floodplain of the study area. Firstly, the pre-project period has been considered. Pre-project period reflects the hydrological situation of the floodplain as it was before 1981-1983 when the FCDI project selected for this study has not been implemented and the floodplain used to be flooded naturally from Madhumati River as well as from adjoining channels such as Bhatiapara channel and from rainfall. Bhatiapara channel used to carry flow of the Madhumati River to the study area floodplain till 1990 and then the area was completely disconnected from the river when the bridge over the channel was replaced with the road embankment after the flood of 1988. The floodplain functions at pre-project situation were natural as the floodplain used to get water from all sources. This has been termed as the pre-project period for the indicator based analysis.

The 2-D overland flow model has been developed for this analysis. The overland flow model produces the hydrological scenario of the study area floodplain during the pre-project situation. The hydrologic output from the modelling are flooded area, depth of water and duration of inundation. Figure 4.24 shows the inundation in overland flow model in the pre-project period. The water depths with respect to timing for pre-project period are given in Table 4.13.

A hydrograph of generated monthly average water depth in the floodplain at pre-project period is given in Figure 4.25. However, generated daily average water depth data of the floodplain at pre-project period are attached in Appendix A.

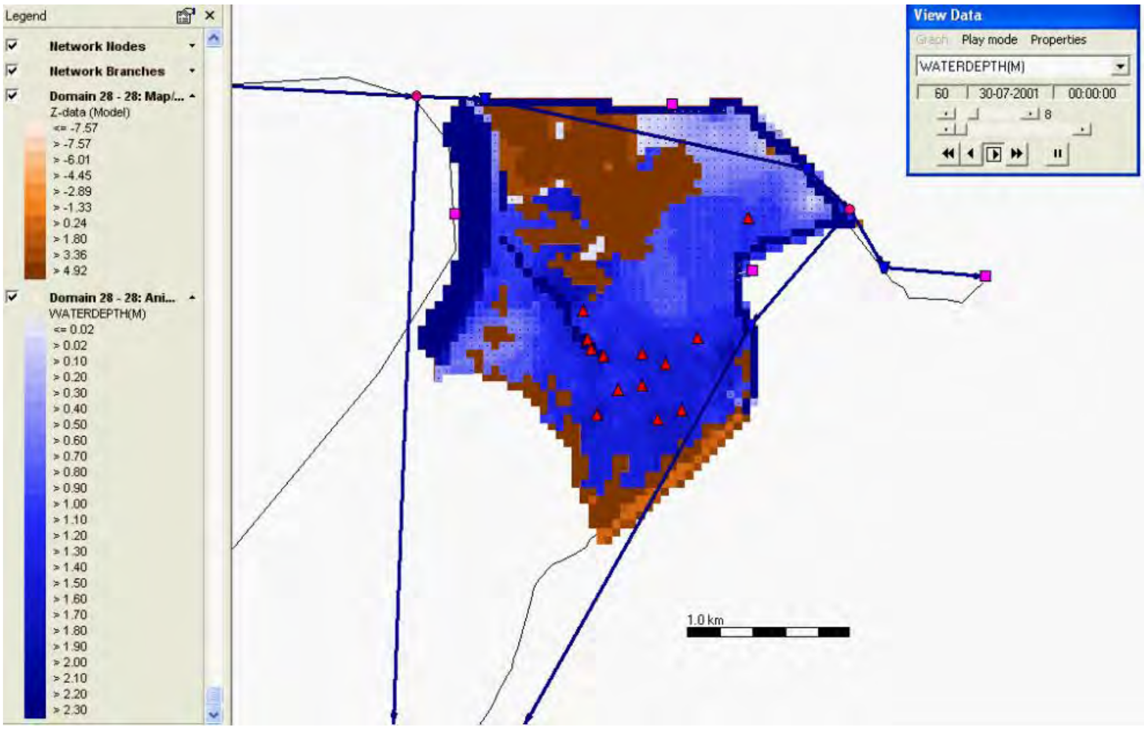

Figure 4.24 SOBEK 2-D overland flow model run for pre-project period

Table 4.13 Monthly average maximum water depths (m) in the study area

Month	Pre-project period	Post-project period
	Water depth (m)	Water depth (m)
January	0	0
February	0	0
March	0	0
April	0	0
May	0.70	0.35
June	1.19	0.50
July	2.54	0.55
August	2.39	0.28
September	2.31	0.20
October	1.94	0.02
November	0.82	0
December	0	0

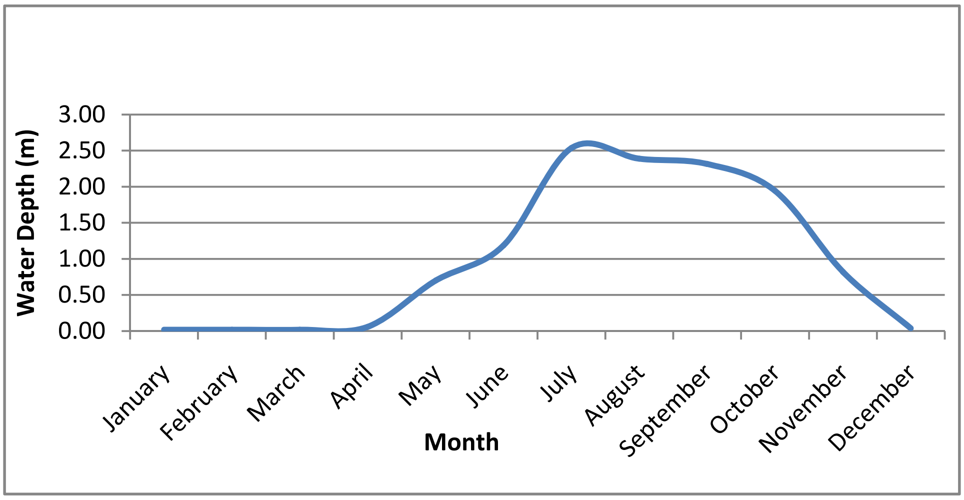

Figure 4.25 Model generated long-term average monthly maximum water depth in the floodplain at pre-project period

Application of rainfall runoff model

The hydrological model 'NAM' is a deterministic, lumped and conceptual rainfall-runoff model accounting for water content up to four different storages. As default, NAM is prepared with nine parameters representing the surface zone, root zone and groundwater storages. The hydrological model has been used to simulate and estimate the depth of water stored in the floodplain when the study area is completely surrounded by polder. The study area is a small portion of Madhumati catchment. Catchment may be defined as an area of land from which rainwater drains into a reservoir, pond, lake, floodplain, river or stream.

Several parameters have been used in NAM model. These parameters have been assumed for different sub-catchment based on the values used for South West Region Model (IWM, 2006). These values are presented in Appendix A. For determining the areal average precipitation and evaporation, weighted average method has been used. The results of NAM model have been calibrated with the groundwater fluctuation graph of the observation well. Figure 4.26 shows the calibration for a catchment with the observation well of groundwater station at Kashiani (GOP 006).

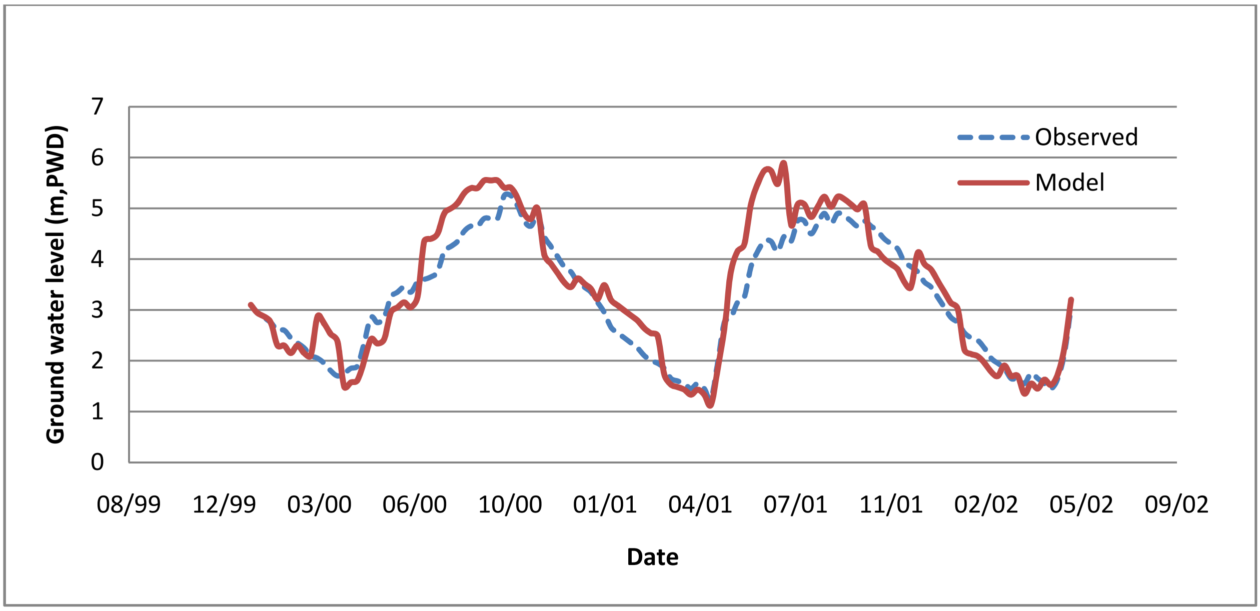

Figure 4.26 NAM model calibration for groundwater level at Kashiani (GOP 006)

Generation of floodplain hydraulic data for the post-project period

When the Purulia Charbhatpara FCDI project was completed during 1981-83 and the Bhatiapara channel was closed with a road constructed in 1990, then the study-area-floodplain has been considered fully closed because most part of the floodplain has been disconnected from the outside water flow sources. So there has been no flow in the floodplain either from Madhumati River or from surrounding channels. Rainfall has been the only source of water in the floodplain. In the indicator based analysis this period has been termed as post-project period. A hydrograph of monthly average maximum water depth in the floodplain has been generated for the post-project period from NAM rainfall runoff model taking rainfall as the only source of water and is shown in Figure 4.27. The water depths with respect to timing for post-project period are given in Table 4.13. However, generated daily average water depth data of the floodplain at post-project period are attached in Appendix A.

Monthly average maximum water depths on the floodplain for pre-project period have been taken as the sum of 2-D overland water depths and NAM rainfall water depths. The pre- and post-project water depths inside the study-area-floodplain are shown together in Table 4.13.

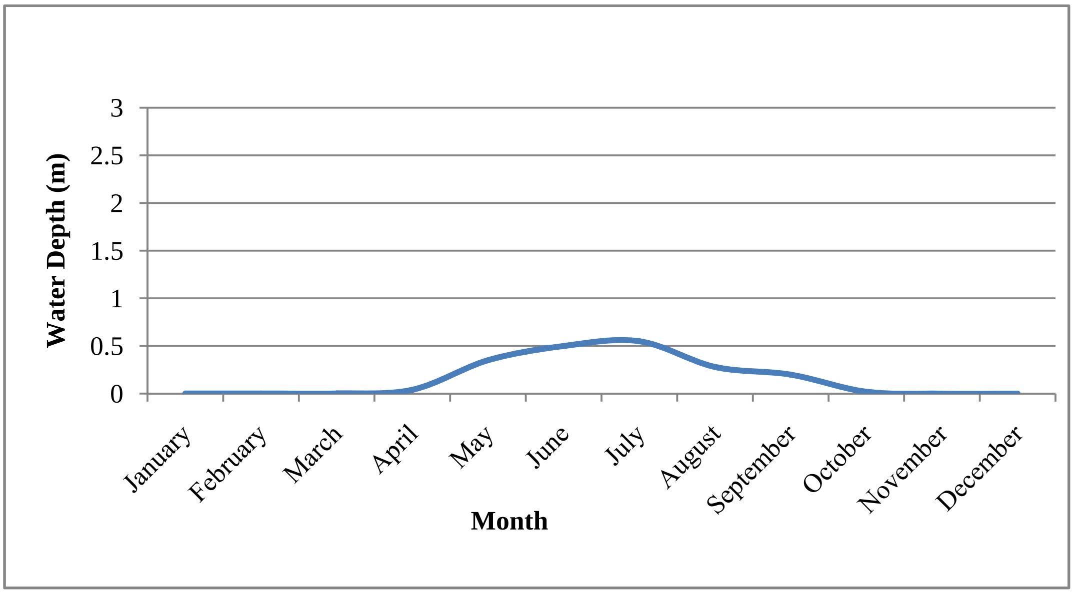

Figure 4.27 Long-term average monthly maximum water depths in the floodplain at post-project period

Estimation of recharge

The recharges have also been estimated from the following logarithmic formula suggested in the Technical Report No 5 of MPO (1987):

Recharge (mm) = A + B log (Annual rainfall (mm))……………………………………….4.6

Where *A* = -3215 and *B* = 1125 for the study area.

The values of *A* and *B* have been taken from the above-mentioned Technical Report. Additional 12.5% recharge, as suggested in the southwest regional model study conducted by IWM (2006) has been taken as recharge from flooding. Recharges have been estimated at 4.84 million cubic-meters and 4.16 million cubic-meters at pre-project and post-project period respectively

4.3.5 Ecological data investigation

Selection of indicator species/group

Selection of species or a group of species or both is a prime important stage for an indicator based ecohydrology study. Floodplain is dynamic in hydrological nature as well as highly diversified with biological community. Both flora and fauna in the floodplain environment have been considered to establish a model ecohydrograph. Considering economic and ecological value of the floodplain resources, three groups of fishes *ie* carp fish, catfish and small indigenous species (SIS) have been selected as the representative groups of floodplain fauna while Broadcast *Aman (B. Aman)* has been selected as the representative of floodplain flora. Selected fauna and flora under the groups is shown in Table 4.14.

Table 4.14 Selected indicator groups for ecohydrograph development

Indicator Class	Groups/Guild	Common Species
Flora	Paddy	*B. Aman*
Fauna (Fish)	Carp Fishes	*Catla catla* *Labeo rohita* *Labio calbasu* *Ciprinus carpio* *Tenopharingodon idela*
	Cat Fishes	*Mystus vitatus* *Mystus aor* *Heteropneutes fossilis* *Clarias batrachus*
	Small Indigenous Species (SIS)	*Rasbora rasbora* *Amblypharingodon mola* *Puntius ticto* *Macrobrachium sp* *Chanda sp* *Colisa fasciata* *Chela cachius* *Gudusia chapra* *Corica soborna*

Hydraulic requirement of the selected individual species/group

Fisheries population and the floodplain crops in Bangladesh are adapted to the variation of flooding and their life cycles are tuned to it. Physical parameter preference, spawning, recruitment and migration pattern and duration along with habitat condition have been investigated for the study. Based on biological requirement (mainly behavior, migration, reproduction and growth) identified in a number of studies (Boyd, 1982; Das, 1998; WARPO, 1995a and EGIS, 1997), three ideal groups of fish *ie* carp, catfish and SIS, and one floodplain crop *ie* Broadcast Aman paddy, presently in practice, have been selected for the present study. On the basis of biological requirement which has been adapted from the above-mentioned studies, water requirement of paddy and fish over a period of twelve months in a year is shown in Table 4.15.

Table 4.15 Hydraulic requirement of carp, catfish, SIS and B. Aman

Ecological species		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Carp	Required water depth (m)				0.5	1	1	1	1	0.5			
	Suitable velocity (m/s)				0.2	0.2	0.2	0.2	0.2	0.1			
	Remarks	Most of the carp species (except Rui) complete their spawning activity by mid of July, while Rui species require time up to August. On the other hand, fingerlings out migration may continue up to September (July to September). They initiate migration in April and complete in September.											
Catfish	Required water depth (m)			0.5	0.5	1	1	1	1	0.5			
	Suitable velocity (m/s)			0.1	0.1	0.2	0.2	0.1	0.1	0.0			
	Remarks	Floodplain residents usually breed in pre-monsoon period of March-April while river species breed during May-June.											
SIS (small indigenous species)	Required water depth (m)				0.3	0.3	0.3	0.3	0.3	0.3			
	Suitable velocity (m/s)				0.1	0.1	0.1	0.1	0.1	0.1			
	Remarks	SIS are highly diversified in biological feature because number of species under this guild is high. Most of them are double breeder (per year).											
Paddy (B. Aman)	Required water depth (m)				0.0	1.2	3.4	3.5	3.5	3.0	0.5		
	Remarks	B. Aman can tolerate 3 inches (0.076 m) of daily water level increase, up to a maximum 3.5 m depth of water.											

(Source: Adapted from Boyd, 1982; Das, 1998; WARPO, 1995a and EGIS, 1997)

The ecological data have been collected from both primary and secondary sources. Hydrological requirement of the indicator flora and fauna were established from different literature and past research. Similarly, physical parameter preference, breeding and recruitment, migration, and habitat situation were obtained from published reports, including report on Fisheries Resource Survey System (FRSS) of Department of Fisheries (DoF), and Bangladesh Fisheries Research Institute (BFRI), as well as from case study, FGD, semi-structured questionnaire survey, market survey, etc.

To establish the general preferences of the fish habitats, some fish species and their physico-chemical parameters have been studied. Most of the carp fish prefer 0.5 to 1.0 meter of water depth where catfish’s preference varies from 0.5 to 2.0 meter. On the other hand, SIS loves comparative low water depth. If water requirement for fish, particularly carp, is met then requirement for other ecosystem will be met. Preference of water depth and timing of spawning migration of some species are shown in Table 4.15.

Field reconnaissance for ecological data investigation

Field reconnaissance has been done in the study area to have a clear conception about the location, people, socio economic activities, project boundary, livelihood of general people, impacts of FCDI intervention particularly on agriculture, fisheries and aquatic ecosystem. This has helped in arranging FGDs and identifying people for interviews.

Rapport building and observation

The study area has been visited several times and the researcher has stayed in the study area for several days during each visit. A cordial relationship has been built up with the farmers, fishers, and other professional group people including women and especially senior people of the area. Through polite meeting, chatting, agreeing with their opinion and comments, normal traditional conversation a rapport has been built up with the local people. Rapport building is necessary to:

- get introduce with the locals as well as with socio-economic and ecological environment of the study area
- understand the local people, local language and local culture
- understand the research area
- collect the most meaningful data within short time
- inspire and encourage local people with a view to making them available with real information.

Rapport building has been done to identify key informant for interview. The perception about social, economical, cultural and ecological condition of the area has been gathered through observation during stay in the study area.

Key informant interview

Key informant interview has been used in the study. People of different professions such as farmer, fisher, trader, teacher, shopkeepers, and woman and of different ages have been interviewed as key informants. A key informant has been selected who is:

- a senior local of between 40 and 90 years old and has a clear idea about the research area
- involved in various activities with the local people or is capable to explain the different activities of the local people
- considered as a neutral person to the local people and is counted as well-wisher of those whose will be studied
- living in the area for a long time and permanent resident as native
- educated and able to explain the observation meaningfully and clearly
- above all, a person of integrity, honesty and responsibility.

Primary data collection

Focus group discussions (FGDs)

Three FGDs have been conducted during the study period. Informal discussion rather than a formal questionnaire has been followed for FGD. The FCDI project history, general impacts of water resources projects, and information on changes in seasonality and water depth, and abundance of fish and other aquatic plants have been collected through FGD. Fulltime fishers, farmers as a subsistence fisher and mixed groups have been invited in the FGD meeting focusing water as the subject of discussion. They all need water for crop production, fish culture and for other uses. Ten to fifteen people have been invited in a discussion. Fishery related information have been collected from fulltime fisher group and also from subsistence fisher (farmer). The details of FGDs conducted for the study are given in Table 4.16.

Table 4.16 FGDs with different groups at different locations

Sl No	Type of respondents	Locations	Date
1	Government officials and elected people representatives	Kashiani Upazila HQ	1 June 2008
2	Farmers, fishers, teachers, shopkeepers,	Shankarpasha Bazar	5 September 2010
3	Members of the water management groups	Bhatiapara Bazar	7 September 2010

Semi-structured interview and key informant interviews (KII)

Fisheries data, specifically taxa number, catch size by weight and the availability of the open water fish species, have been collected using semi-structured questionnaire emphasising on fulltime fisher than subsistence fisher. Some KI people have been used for sharing and fulfilling the gaps of both FGD and semi-structured interviews. Nazimuddin (2005) suggested method for PRA tools (mainly semi-structured questionnaire) in biodiversity indexing for fisheries and agro-crops. The same method has been followed in the study along with FGD and KII. The details of the conducted semi-structured interviews and KII are given in Table 4.17. Interview with a senior farmer and a fisher-cum-farmer is shown in Figure 4.28. The semi-structured interview regarding the capture fisheries and fish habitat are given in Appendix C.

Table 4.17 List of interviews with interviewee

Sl No.	Type of Interview	Interviewee
1	KII	Fisherman
2	KII	Retired govt. officials
3	KII	Gate operator (regulator)
4	KII	Local farmers
5	Semi-structured questionnaire interview	Upazilla Fishery Officer and Agriculture Officer, Kashiani Upazilla, Gopalganj

Figure 4.28 Key informant interview in the study area

Fisheries biodiversity analysis

Fish market survey

Extensive market survey (six visits in three occasions) has been carried out in two major fish markets in Bhatiapara Bazar and other local markets to record the fish species found in the locality and also to get the information about natural and culture fisheries status.

Fish sampling

Beside PRA and market survey, primary field fish sampling has been done to get the actual present fisheries biodiversity status, production status and the habitats' productivity of the study area and also to make a triangulation among the methods. Samples have been collected in three seasons *ie* pre-monsoon (April-May), monsoon (June-August) and post-monsoon (September-October). Samplings have been carried out at 6 suitable points. The fish samples have been collected from each station by using common gears. Then the fish have been taken into sorting and identification, and counting. Fish sampling, sorting and identification, counting, and market survey are shown in Figure 4.29.

Sorting and identification and counting

Sorted fish have been identified and enumerated under major taxa. For identification of species, standard methods have been followed and results are given in Appendix B.

Figure 4.29 Fish sampling, sorting and identification, counting, and market survey

Measurement of biodiversity: Biodiversity index

Four biodiversity indices namely taxa, individual, species diversity, and species dominance have been studied for the research. Shannon-Wiener diversity index and Simpson dominance index are described below:

Shannon-Wiener diversity index

The Shannon-Wiener diversity index (H) is commonly used to characterise species diversity in a community. The proportion of species *i* with respect to the total number of species (represented by p_i) has been calculated and then multiplied by the natural logarithm of this proportion. The resulting product is summed across species, and multiplied by 1. The formula (Shannon and Wiener, 1949) is shown as below:

$H'' = -C\sum P_i(\ln P_i)$……………………………………………………………………4.7

where, H'' = Sample diversity index

$\sum$ = Sum of the values of parameters (i = 1, 2, 3, ...s)

P_i = Proportion of i^{th} species in the sample

ln = Natural logarithm

C = Constant (It is customary to put C=1.)

The S-W Index values (H) can range from 0 to 4.6. A value near 0 would indicate that every species in the sample is the same. Conversely, a value near 4.6 would indicate that the numbers of individuals are evenly distributed between the species. High values of H would be representative of more diverse communities. So H value allows us to know not only the number of species but also the distribution of the species.

Simpson dominance index (D)

Simpson dominance index (D) has been calculated by the following formula (Simpson, 1949):

$D = 1 - \left[\sum n_i(n_i - 1) / N(N - 1)\right]$ ……..4.8

where, D = Simpson dominance index

N = Total number of individuals of all species in the community

n_i = Number of individuals of the i^{th} species

The values for dominance index range from 0 to 1 where a sample of equal numbers of individuals of the same species has a value of 1.

4.3.6 Ecosystem dependent livelihoods

Floodplains are rich in ecological resources that produce important services for the local people particularly for the poor. A majority of the people of Bangladesh are critically dependent on wetlands for their livelihoods (Talukder *et al*, 2009). The livelihood of many people of the study area especially the poor living around the beel area have been dependent on the resources of this wetland.

In the recent past, professional fishers were dependent on wetlands to earn their livelihoods by harvesting fish. However, later on millions of poor and landless households were deprived of their right because of land use change and decline of ecological resources (Mahfuzuddin, 1993). The degradation of resources in wetland ecosystems is more rapid than that in other ecosystems in Bangladesh (Hector *et al*, 2005).

4.3.7 Flood flow dependent ecological resources

Flood flow dependent ecological resources include both fauna and flora. Many fish species such as carp, catfish and small indigenous species are among the fauna and many edible plants mostly wild vegetables, some aquatic plants as the shelter of fish and other aquatic organisms are among the flora. In the study area ecological resources are mainly different types of fish, crab, turtle, bird, snail, oyster, mollusc, water lily, etc.

4.3.8 Floral and faunal habitat conditions

Fisheries resources of the study area are diversified with different fresh water fish habitats. Open water fish habitat of the study area includes river, channel (khal), beel and floodplain. Bhatiapara channel, Dhalsree channel, etc act as the major artery of fish migration into the study area. These are playing vital role in maintaining fisheries productivity of seasonal and perennial water bodies like Sorderer Gup and Dhalsree beel and floodplains.

Madhumati is the only river of the study area. The area consists of a number of seasonal water bodies–Dhalsree beel and Sarderer Gup beel. These are mostly concentrated in Ratail union. Among these two, Dhalsree beel is important. Besides, Bhatiapara channel and Dhalsree channel are important habitats in the study area. Average depth of internal canal is between 1.5 meters and 2 meters and this is sufficient for fish habitation. Depth of seasonal beels of the study area is enough for sheltering fish juveniles.

River, beel, channel, canal and floodplain are used as breeding, feeding and shelter ground for most of the riverine and floodplain fish. Many fish species migrate horizontally to these water bodies as part of their life cycle. Many canals are silted up naturally, which reduce the length of successive migration routes. Migration time of the floodplain fish, with respect to both in-migration and out-migration, is very important for the ecological sustenance. General in-migration time of the selected groups of the floodplain fish species starts from late April to August; and out-migration time continues from August to early November. The study area is moderately rich in fish biodiversity. But the trend is declining slowly. This is mostly due to habitat loss, loss of connectivity, indiscriminate fishing, poor fisheries management, etc. Fresh water fish occupy the whole catch composition from different habitats. Small indigenous fish and catfish are the dominant fish of the catches.

Chapter 5

DATA ANALYSIS AND ASSESSMENT OF IMPACT OF EXISTING FLOOD CONTROL PROJECT

5.1 Data Analysis

The study area, sources of data and collection of both topographical and ecological primary data are described in Chapter 4. Acquisition of historical land-use data and hydrological and ecological data from secondary sources and method of primary data collection are also described there. Data analysis and assessment of impact of FCDI project at pre- and post-project periods are described in this chapter. Changes in land-use, floodplain hydrology and functions, land type and fish habitat, fish production, and biodiversity are enumerated here.

5.1.1 Land use data analysis

Land-uses of the study area have been classified into four broad categories namely agriculture, settlement, road, and water body. Road includes kancha (made of earth) road, pacca (paved) road and halot (narrow kancha road). Water bodies are mainly of internal canal and pond. Present land-use of the study area has been analysed from Google satellite image of 2007 as shown in Figure 4.3. Pre-project land-use of 1941-43 and post-project land-use of 1985-87 are shown in Figures 4.6 and 4.7. Different land-uses of various periods have been estimated and are shown together in Table 5.1.

Table 5.1 Present, post-project period and pre-project land-uses

Land use		Unit	Present (2007)	Post-project (1985-87)	Pre-Project (1941-43)
Settlement		ha	311	298	272
Agriculture		ha	798	816	850
Pond, canal		ha	11	9	3
Road		ha	22	19	17
	Total	ha	1142	1142	1142

The pre-project, post-project and present land-uses are shown in percentage in Figures 5.1, 5.2 and 5.3, respectively.

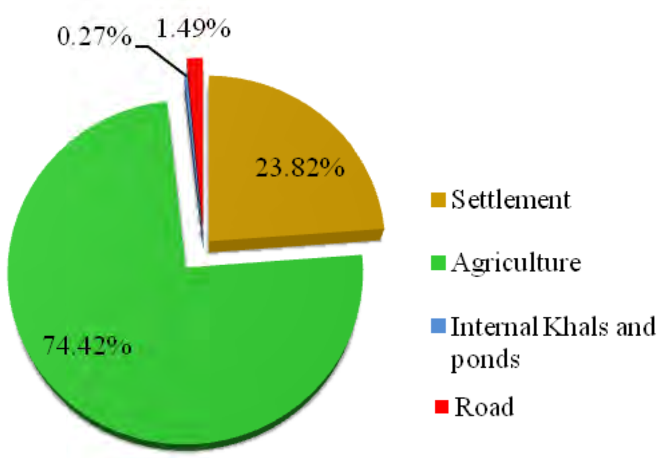

Figure 5.1 Pre-project land-uses in percentage

The area of the study area has been calculated at 1142 ha. At present agricultural area covers about 798 ha, settlement area around 311 ha, road 22 ha, and internal canal and pond 11 ha. In pre-project period agriculture was the dominant land-use. There were a few ponds and no canal and a few roads in the study area. Settlements were relatively low. Agriculture has been the dominant land-use being 74.42%, 71.45% and 69.88% during pre-project period, post-project period and present condition respectively. It has been decreasing slowly because of conversion to other land uses mostly to settlements.

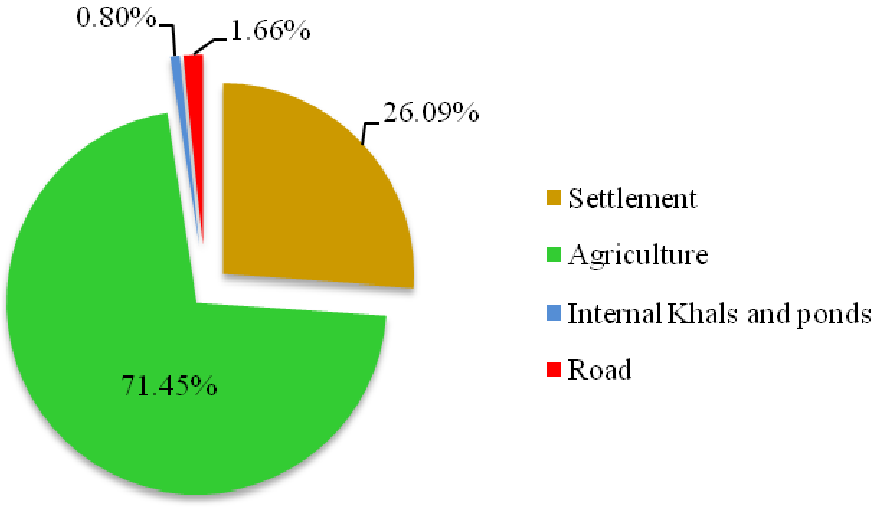

Figure 5.2 Post-project land-uses in percentage

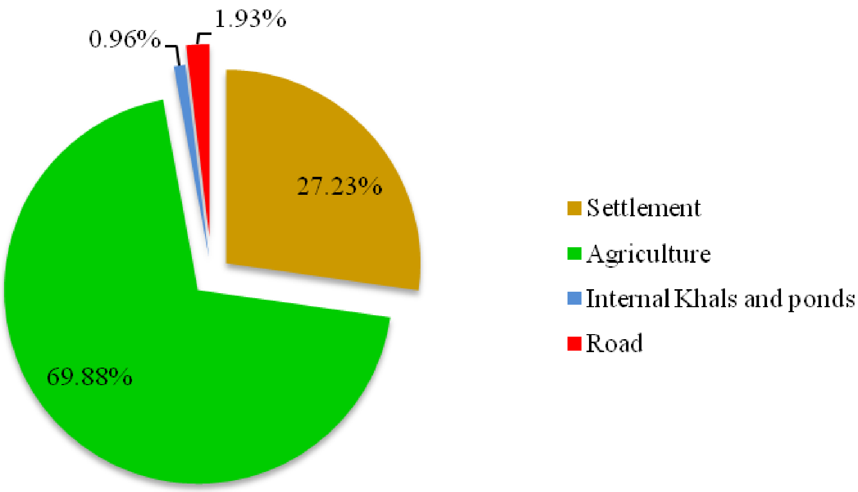

Figure 5.3 Present land-uses in percentage

Other three types of land-uses have been increasing slowly. Number of ponds and area as well has increased as people dug ponds for various needs. A canal through the middle of the study area was excavated under the FCDI project (Figure 4.1). Rural roads have been constructed over time. Presently, agricultural land continues to convert to other land-uses. Settlement increased by about 4% between pre-project and post-project periods and by about 8% between 1981-83 and 2007. Similarly agricultural area decreased by 2% and 4% respectively from pre-project period to post-project period to present time.

5.1.2 Hydrological data analysis

The Monthly average maximum water depths in the study area during pre-project and post-project periods have been generated and estimated using hydrodynamic model and rainfall runoff model and tabulated (Table 4.13). From the pre-project and post-project hydrographs (Figures 4.25 and 4.27), it is easily visible that there is a large reduction in depths of water in the study-area-floodplain during the post-project period. This has happened because the study area has lost channel connectivity with the Madhumati River.

The land type of the study area has been analysed for pre-project and post-project periods. For pre-project period, the land type data have been developed from the average water level data of the river and canal generated by running the SOBEK hydrodynamic model. Under pre-project period the study area is found with much water and about 63% of the total area is flooded. In this case F0 land is only 321 ha out of total 1142 ha. Figure 5.4 shows the land type during pre-project period, *ie* natural period, when there was no flood management intervention.

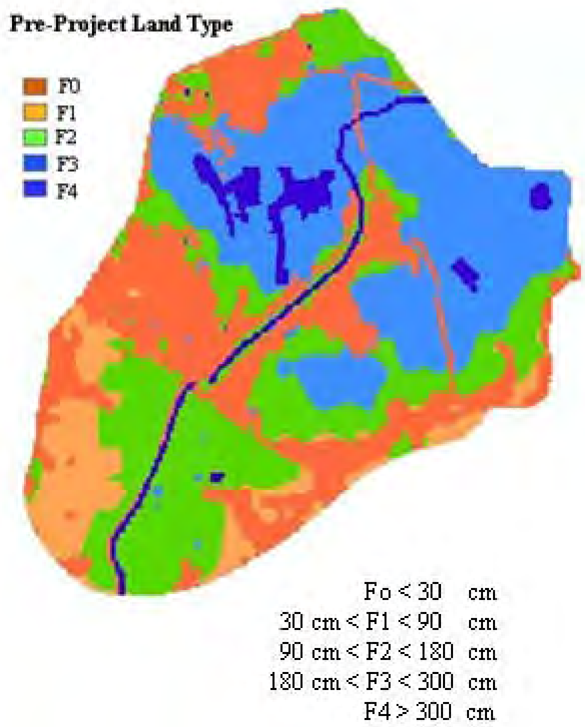

Figure 5.4 Land type in pre-project period

Land-type generated for the post-project period is shown in Figure 5.5. The flooded area has been much reduced and is only 26% of the total area. The post-project land type distribution has been developed from the storage elevation relation. The storage has been calculated from the rainfall runoff model.

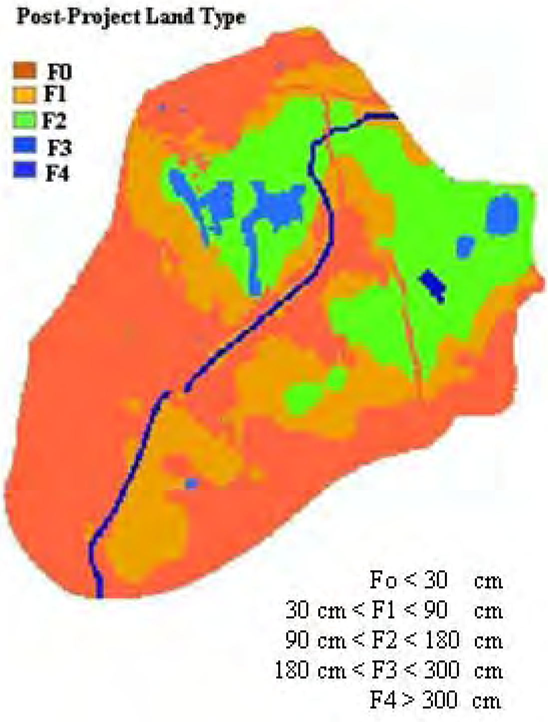

Figure 5.5 Land type during post-project period

Changes in land-type between pre-project and post-project periods are shown in Table 5.2. Water depth during post-project period has decreased significantly. F0 and F1 types land increased during post-project period. On the other hand F2, F3 and F4 land types, habitat of fish and other aquatic biota, have reduced greatly. This has significant impact on the health and production of aquatic biota particularly on fish and edible plants.

Table 5.2 Change in land type

Land Type	Area (Ha)		
	Pre-Project	Post-Project	% change
F0	321.24	565.78	76.04
F1	102.24	276.82	170.85
F2	314.44	240.58	-23.45
F3	351.48	36.50	-89.58
F4	52.60	22.32	-57.72
Total	1142	1142	

5.1.3 Ecological data analysis

The ecological data have been collected from both primary and secondary sources. As can be seen in Table 4.15, most of the carp fish prefer 0.5 to 1.0 meter of water depth where catfish's preference varies from 0.5 to 2.0 meter. On the other hand, SIS requires comparative low water depth. The majority of fresh water fish breed during the monsoon months *ie* between May and August because of their dependency on seasonal floods, which inundate the floodplain essential for reproduction, feeding and living. Fisheries data collected through sampling, sorting and identification, and counting have been analysed; and fish biodiversity and dominance have been calculated.

5.2 Impact Assessment

Based on the data and their analyses, impacts on functions and indicators of floodplain hydrology and impacts on faunal and floral habitat, biodiversity, and production have been estimated. The results are presented in the following sections.

5.2.1 Impact on floodplain hydrology

Hydrological functions of the floodplain include water flow regulation, connectivity between river and floodplain, regeneration of underground water, floodplain flow sustenance and amount of wetland area. The indicators against these functions have been selected as maximum water depth in the floodplain, conveyance, duration of flow to the floodplain, groundwater recharge, maximum flow in the floodplain, and flooded (beel) area in the floodplain. The hydrological data of the study-area-floodplain such as depth of water, extent of flood, discharge and velocity have been generated from the overland flow model. These data have been used to determine different hydraulic and ecological functions of the study area floodplain. Rainfall contribution as flood to the study area has been estimated using rainfall runoff model. Data relating to regeneration function of the floodplain have been estimated using the recharge model. Maximum water depths have been taken from Table 4.13, flood area and beel area values from Table 5.2, values of conveyance characteristics of the channel and canal from field survey, flow duration value from model, and recharge value has been estimated using

Equation 4.6. The values of these indicators for pre-project and post-project periods are tabulated in Table 5.3.

Table 5.3 Pre-project and post-project values of hydrologic indicators

Functions	Indicator		Unit	Pre-Project	Post-Project
Regulation	Maximum average depth in floodplain		m	2.54	0.55
	Flooded area (F2+F3+F4)		%	63	26
Connectivity	Conveyance characteristics (from field survey)	Bhatiapara channel	sq m	342	0
		Internal canal	sq m	273	240
	Duration of flow in connecting river/channel with floodplain/beel (from model)		day	175	0
Regeneration	Recharge (estimated from equation)		Mm^3	4.84	4.16
Floodplain sustenance	Maximum flow in the floodplain (from model)		$m^3/s/m$	0.28	0
Biodiversity	*Beel* area (F3+F4)		ha	404	59

Indicator-wise impacts on the floodplain because of the flood management project are described below:

Imapct on flow regulation function

Indicators under flow regulation function are maximum water depth and flooded area of the floodplain. As can be seen in Table 5.3, maximum depth of water of 2.54 meter in pre-project period reduced to 0.55 meter at the post-project period. Post project water depth is much below the minimum requirement of carp and catfish; it can only sustain small indigenous species (SIS) of the study area. Flooded area reduced from 63% in the pre-project period to 26% at the post-project period. This has significant bearing on the health, movement, growth, and production of fish and other aquatic plants such as water lily, which is used as vegetables by many poor people in and around the area.

Impact on river and floodplain connectivity function

Conveyance characteristics of the connecting channel/canal between the river and the floodplain and duration of flow in the floodplain are taken as the indicators of the connectivity function. The cross-section area of the Bhatiapara channel and Dhalsree internal canal have been measured during the field survey as the conveyances characteristics. As evident in Table 5.3, in post-project period, the conveyance of the Bhatiapara Channel has been considered nil because it is disconnected from the river since 1990. This has caused a serious damage to the ecosystem of the study area floodplain. The study area has been transformed to a static water body from a dynamic river-floodplain system. Exchanges of nutrient and organic matter and sediment/larvae/egg between the Madhumati River and the study-area-floodplain stopped, disturbing the mixture and distribution of nutrients and plant communities. Besides, in-migration route for juvenile and out-migration route for adult fish also diminished. The fish community in particular has been reduced in number and in its production. Again, because of siltation, the conveyance of the internal canal has been reduced. This has reduced the internal movement of a few species of the survived fish inside the study area. The model estimated a duration of flow of 175 days in the study-area-floodplain in the pre-project period. After project, the connection has been lost and there has been no flow inside the study area. The species mating, spawning and growing up and bed load transport and waste disposal have been stopped. Therefore fish production and biodiversity have been reduced.

Impact on groundwater regeneration function

Recharge has been taken as the indicator for groundwater regeneration function. Two types of recharges have been considered—recharge from rainfall and recharge from flooding. Recharge estimates at pre- and post-project periods are shown in Figure 5.6. Recharge of 4.84 million cubic meters in pre-project period has been reduced to 4.16 million cubic meters at post-project period. Due to the loss of connectivity between the river and the study-area-floodplain, recharge from flooding during post-project period has been almost reduced to nil. During this period the only source of recharge has been the rainfall.

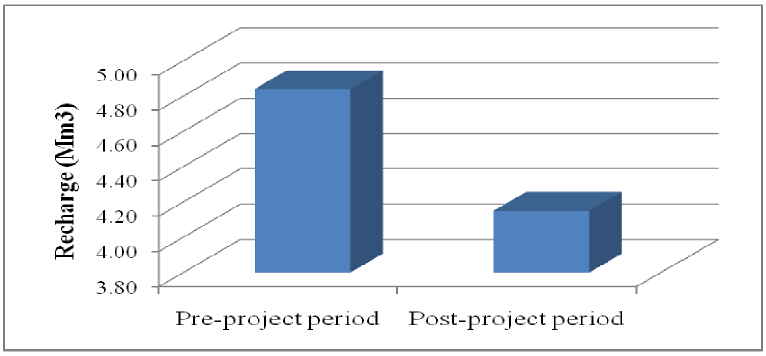

Figure 5.6 Comparison of recharge in different periods

Recharge was much higher during pre-project period as recharge took place from both rainfall and flooding. Because of reduction in recharge, groundwater table in post-project period went down causing harm to the benthic community and reduction in groundwater availability for irrigation.

Impact on floodplain sustenance and biodiversity functions

For the sustenance of floodplain, maximum average discharge has been taken as the indicator. The model estimated maximum flow in the floodplain as 0.28 m^3/s/m in the pre-project period. Due to connectivity loss, flow in the floodplain has been reduced to nil in the post-project period.

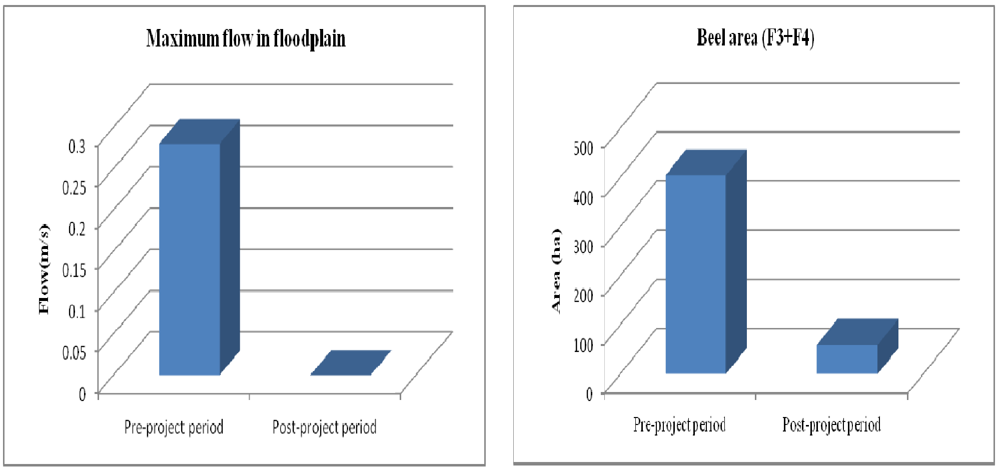

Figure 5.7 Comparison of flow and biodiversity in different periods

The amount of wetland area or *beel* area indicates the richness or poorness of biodiversity. The model results showed that during the pre-project period beel area has been as high as 404 ha while it reduced to only 59 ha at the post-project period. This corroborates with the findings of reduction in biological production and biodiversity in the study area during the field survey. A comparison of flow and *beel* area between pre- and post-project periods is shown in Figure 5.7.

From key informant interview it has been found that fish have been reduced significantly. Poor people catch small fish and sell them in the market for livelihood. Mollusc (shamuk), inside the project, has been in abundance earlier but now decreased because water inside the project area has been much reduced. Water cannot enter into the beels as the connection between the floodplain and the river is totally lost. Rain water is only the water they depend. During two-three months of Ashad-Shraban-Bhadra, poor people catch mollusc.

Fish have been reduced to almost nil. Fish such as boal, chitol, chingri (prawn) all disappeared. Local sorputi, baila, big chingri (prawn) are not available now. Connection between river and canal is lost. Water and fish cannot enter into the beels. So fish have been reduced. Jute could not be rotten because of no water. This is an every year problem; cost of jute production increased and hence many farmers abandoned its cultivation.

Fishermen have been compelled to change their livelihood. They became van pullers and day labourers. Shapla, kolmi shak reduced. Due to lack of river silt, more fertilizer is required and the land got polluted. Because of no tide and no inundation or flood, silt from the river cannot enter into the beels or fields; therefore wheat, *til* (oil-seed), lau and kumra (cucumber) could not be cultivated. Chhola (pea) migrated from the project to riverside lands.

Lal digari, kalo digari, and maita digari (kind of Siberian duck) would come in the area every winter but stopped because of no water. Dahuk, koda also reduced. If Bhatiapara khal could be reopened, then fish would come in Kusundia, Vadulia beels from the Madhumati River.

5.2.2 Impact on ecology due to flow alteration

Change in land use pattern and alteration of floodplain hydrology over the last 30 years have reduced the ecological resources and common property areas of the study-area-floodplain. During the pre-project period there had been a minimum of 4-5 feet of water in the bottom part of the beel areas in the dry season. Many senior people in the study area have reported that they could not catch all the fish during pre-project time even in the driest period of the year because of much water in the deeper parts of the study area. But the flood protection embankment has stopped water flow inside the project and now there is little water in the deepest part of the beel. So, people have caught most of the fish including mother-fish. Therefore there are a few species left in the beel. Poor professional fishers have been forced to change their profession from fishing to other jobs like day labour, rickshaw pulling, etc. Ecological functions such as faunal habitat, migration support, biodiversity, and habitat productivity with specific indicators for pre- and post-project periods have been estimated and are shown in Table 5.4.

Table 5.4 Ecological functions and indicators at pre- and post-project periods

Function	Indicator	Duration	Unit	Pre-project period	Post-project period
Fauna habitat maintenance	Area (F2+F3+F4)		ha	720	300
	Max average depth	April to September	m	2.54	0.55
	Max average velocity (from model)	April to September	m/s	0.2	0
	Seasonality/Connectivity	Annual	day	175	0
Fish migration support	Channel condition	April to September	Length (km)	9.5	5.5
	Migration pattern	April to September		Long+ Lat	Lat
	Spawning migration	April to September	month	5	0
	Hatchling migration	April to September	month	5	0
Biodiversity conservation	Species variation	Annual	Indicative species (number)	48	19
	Species dominance	Annual	Individual dominance	High Low	Low High
Fish production	Yield	Annual	MT	186	53

Impact on faunal habitat

Changes in habitat occur because of alteration of the hydrology and hydraulics of floodplain. The changes can be attributed mostly to three different yet interrelated concurrent direct/indirect impacts of water resources projects: changes in land-use and land-type, changes in water depth, connectivity and seasonality, and anthropogenic actions destroying the fish sheltering places. The study area suffered all these three impacts because of the flood management project.

Land-types F2 (water depth, 90-180 cm), F3 (180-300 cm) and F4 (>300 cm) have been considered as fish habitat. Depth of water is also an important habitat indicator for fish. Fish habitat of 720 hectare during pre-project period reduced to 300 hectare at post-project period which has been practically converted into F0 and F1 types land because flood protection triggered agricultural and settlement intensification. These are shown in Table 5.5. Habitat loss has affected fish productivity, health, movement, and species diversity. Reduction in habitat and deopth of water in the study area floodplain have caused reduction of fish and other aquatic vegetables such as water lily.

Table 5.5 Changes in land-types in pre- and post-project periods

Habitat type	Area (ha)	
	Pre-project period	Post-project period
F0 (<30cm)	321.44	565.88
F1 (30-90cm)	102.24	276.92
F2 (90-180cm)	314.44	240.68
F3 (180-300cm)	351.48	36.6
F4 (>300cm)	52.8	22.32
Total	1142.4	1142.4

Impact on faunal migration and channel connectivity

Faunal migration support was severely obstructed because of reduction of channel length after the project implementation. Channel condition *ie* channel length of 9.5 km in pre-project period has reduced to 5.5 km at post-project period which is almost 50% less. Faunal migration pattern, especially for fish fauna, was changed from longitudinal and lateral to lateral migration only mainly because of loss of connectivity from 175 days in pre-project period to almost zero at post-project period. The channel condition and seasonality of the study area are shown in Figures 5.8 and 5.9

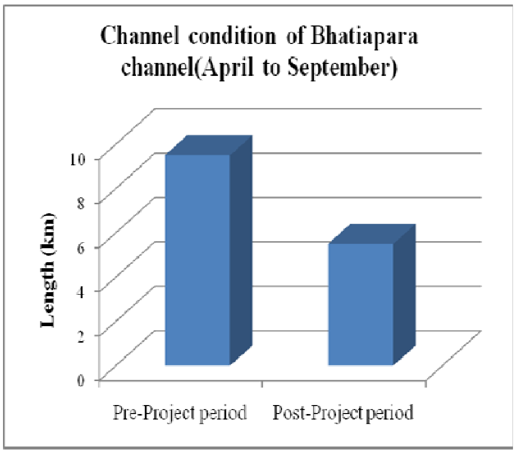

Figure 5.8 Comparison of seasonality condition

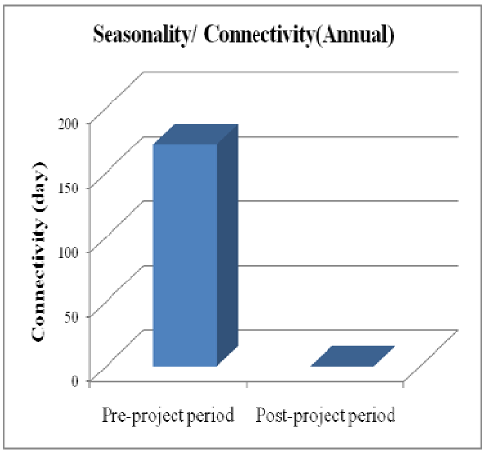

Figure 5.9 Comparison of channel

Recruitment of new species in the study-area-floodplain is the prime important process for habitat productivity maintenance and ecological sustenance. Spawning and migration is the vital steps of faunal recruitment process. Duration of spawning and hatchling migration has been reduced from 5 months in pre-project period to nil in post-project period which caused severe threat to the floodplain ecosystem. Spawning and hatchling migration pattern are shown in Figures 5.10 and 5.11.

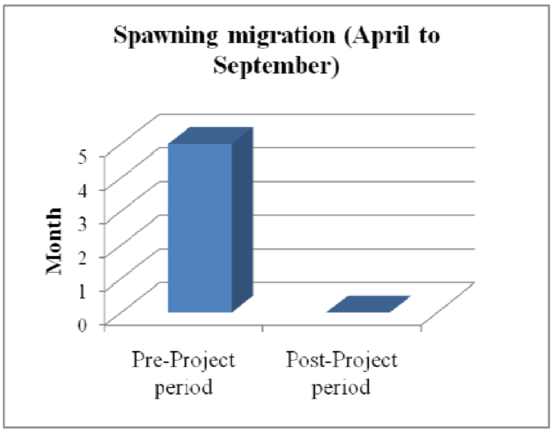

Figure 5.10 Comparison of spawning migration

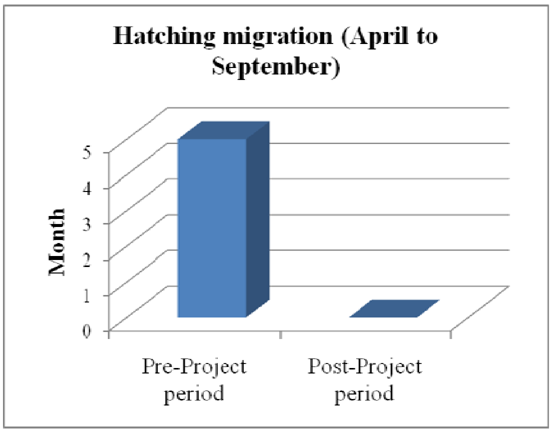

Figure 5.11 Comparison of hatching migration

Impact on fish production and productivity

The yearly fish production in the study-area-floodplain has been reduced from 186 MT in pre-project period to 53 MT in post-project period. This great reduction in fish production has occurred due to loss of habitat for flood management intervention. Fish production of different habitat types is shown in Table 5.6 and comparison in habitat productions is presented in Figure 5.12. Fishery Resource Survey System (FRSS), Department of Fisheries (DOF) estimates annual fish yield and production for each district of the country. Fish yield of 1984 for Gopalgonj District has been taken as pre-project fish yield (DOF, 1984) and fish yield of 2010 has been taken as post-project yield (DOF, 2010) as shown in Table 5.6. The reduction caused because of decrease of fisheries habitat as well as deterioration of the natural production capacity which is reflected in the productivity data.

Table 5.6 Changes in fisheries production and habitats productivity in the study area

Habitat type	Yield (kg/ha)		Production (MT)	
	Pre-project period	Post-project period	Pre-project period	Post-project period
F2	244.38	160.00	76.84	38.51
F3	244.38	160.00	85.90	5.86
F4	450.13	399.00	23.77	8.91
		Total	186.51	53.27

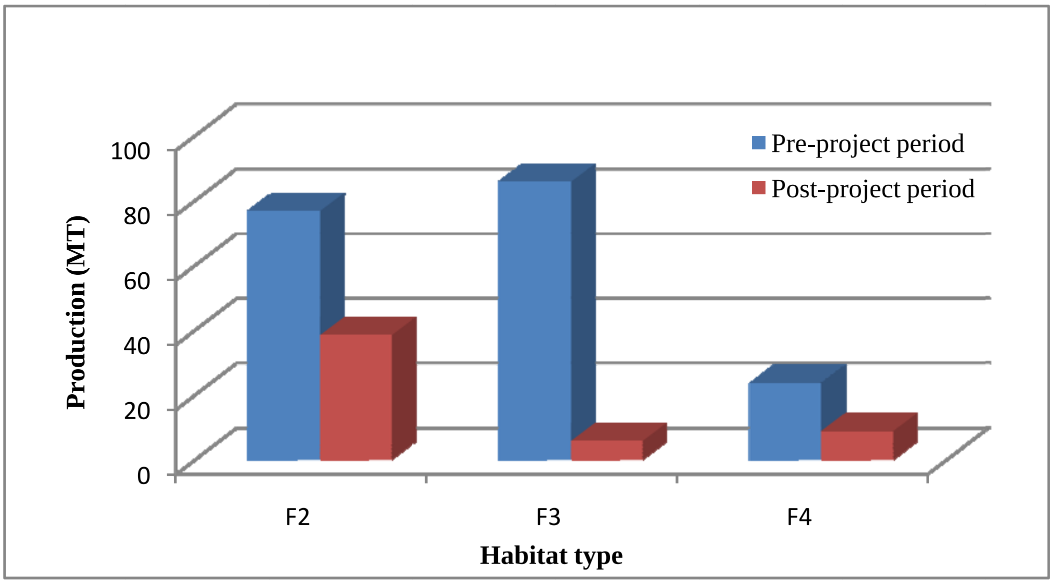

Figure 5.12 Habitat-wise production at different periods

It is evident that the impact on overall fisheries productivity in the study area floodplain (F2, F3 and F4 land types) has been negative. The perennial water bodies of the study area (F4 and part of F3) were more than 4 times productive than the floodplain (F2 and part of F3). The productivity of the study area used to be governed by the perennial part of the study area. Here, loss of perennial water bodies has been responsible for the reduction in fisheries productivity. The productivity has been reduced by 34%.

Changes in fisheries biodiversity

Species Taxa (*Taxa_S*): In the study area, the species taxa ranges between 10 (pre-monsoon) to 19 (post monsoon) while it has been found 35 in local market survey. More species have been found in the market because fishermen brought them in the market from the open beels surrounding the study area. Primary fish sampling yielded species count approximately half of the recently reported species count in the literature, and also around 50% lower than species count from market survey. The PRA survey results also support it strongly. The PRA result on the fish taxa has showed that the number of taxa has been reduced over the last 30 years. The species list from field sampling and market survey is tabulated in Appendix B.

The number of fish and shrimp species found from field survey has been far below than 57 species reported by BWDB (BWDB, 2005). Fish species status of Bangladesh and the study area and its surrounding is given in Table 5.7. Earlier, Rahman *et al (*1999) reported 60 species of fish in three floodplains of Chanda Beel, BSKB (Barnal Salimpur Kola Basukhali) and Halti beel in the south-west region near Narail and Gopalganj. Haque *et al* (1996) identified 50 species in two oxbow lakes in south-west Bangladesh, while Mustafa (2009) recorded 46 species in Narail by market survey and 28 species using floodplain fish sampling.

Table 5.7 Fish species status (Taxa_S)

Sl. No.	Report level	No of Species reported	Sources
1.	Overall Bangladesh (indigenous spp)	256 fish 20 shrimp/prawn	Aguero *et al*, 1989
2.	SW region (Narail)	57	SWAIWRMP, (BWDB, 2005)
3.	Narail Dist	46	Market survey, Narail (Mustafa, 2009)
4.	Narail Project sites	28	Sampling sites, Narail (Mustafa, 2009)
5.	Market survey	35	Project sites, Present study
6.	Project Location	19	Sampling sites, Present study

Biodiversity indices

Shannon species diversity index (*Shannon_H'*): Comparatively lower diversity has been observed in the study area (Table 5.8). Shannon index varies from 0 to 4.67 and 3+ has been considered good for Bangladesh (Mustafa, 2009). From the study, Shannon index value has been found at 2.023, which is lower than the average. Therefore the biodiversity of the study area has been reduced.

Table 5.8 Status of fisheries biodiversity in the study area

Sl. No	Diversity Parameter	Value
1	Taxa_S	19
2	Individuals	402
3	Shannon_H	2.023
4	Simpson_1-D (Dominance)	0.796

Simpson dominance index *(Simpson_1-D)*: Higher dominancy (0.796) has been observed in the study area (Table 5.8). Simpson index value ranges from 0 to 1 where a higher value indicates degraded ecosystem. The observed Simpson index value indicates a degraded ecosystem of the study area. This may be attributed to change in land use and/or land type and subsequent fish habitat alteration in the study area. The land type changed from high flooded land to moderate to low flooded land resulting in the loss of natural habitat for a number of species resulting in dominance for crustaceans.

According to de Graaf *et al* (2001), the proposed biodiversity index uses prawns as an indicator for loss of bio diversity or “health status” of the water body, whereby an increased percentage of prawns indicates deterioration. Part of the concept is that beel resident species are replaced by prawn and snakeheads/catfish, once the status of the water body deteriorates. Similar indication has been found from the present study.

Chapter 6

APPLICATION OF DECISION AID FRAMEWORK IN THE STUDY AREA

6.1 Required Hydraulic Condition for Sustenance of Floodplain Ecosystem

The floodplain ecosystem is complex and highly diversified in the context of hydrology and land resources, and undoubtedly supports biological diversification. This complex system is highly influenced and governed by flood. Being a country of rivers and floodplains with high potential of natural resources, paddy and fish play an important role in livelihoods and economy of Bangladesh.

The floodplains, which inundate during monsoon, are nutrient and food rich and play a significant role for 4-5 months of the year (de Graaf *et al*, 2001). Extensive seasonal flooding by high water levels during the monsoon generally occurs between July and November. This flooding has high variation in terms of timing, duration and intensity. Together with the extremely high monsoon rainfall in some year, it creates a highly dynamic floodplain system (de Graaf *et al*, 2001). On the other hand, water areas decline rapidly during the dry season (December-April), which is characterized by very low rainfall and high evaporation rates. This contraction and expansion of aquatic habitats greatly influences floodplain production especially paddy and fish.

As already discussed, fisheries population and floodplain crops in Bangladesh are adapted to these variation and their life cycles are tuned to it. They need different flow and depths of water for migration, reproduction and growth. Considering these requirements, three groups of migratory and floodplain resident fish *ie* carp fish, cat fish and small indigenous species (SIS), and one floodplain crop *ie* Broadcast *Aman* paddy, presently in practice, have been selected for the present study and for the application of the decision aid framework in the study area; and their required hydraulic condition over time *ie* ecohydrological relationship has been determined (Table 4.15).

6.1.1 Maximum water depth tolerable for paddy

Historically, Broadcast *Aman (B. Aman)* is the floodplain rice variety in Bangladesh. This local variety is capable to grow and produce in high water depth. The variety is generally sown in just pre-monsoon singly or along with local rice called *Aus.* Once the rice is germinated and grown up to 10-12 inches, then it is capable to grow with increment of water level at the rate of 3-4 inches daily. In the way of water level increment, at rate of not more than 4 inches daily, the rice can thrive extremely up to 3.5 meters of water which is below the general flooding depth of Bangladesh.

6.1.2 Minimum water depth required for fish

Floodplain and riverine fish species have been categoriesd into three groups for best representation of the fish-fauna for this study. Water is an essential life supporting element for fish and other aquatic fauna. Unlike the selected paddy, minimum depths of water required for the selected groups of fish *ie* carp, catfish and SIS have been considered.

Most of the carp species (except Rui) complete their spawning activity by mid of July, while Rui species spawn up to August. On the other hand, out migration of fingerlings may continue up to September (July to September). Migration begins in April and ends in September. Floodplain resident breeders usually breed during pre-monsoon flood of March-April and river breeders breed in May-June. Small indigenous species (SIS) are highly diversified in biological feature because of high number of species falling under this guild. Most of them are double breeders in a year.

Considering the maximum tolerable water depth, a generalised hydrograph for the *B. Aman*, and hydrographs for carp, catfish, and SIS taking minimum requirement of depth of water have been constructed and are shown in Figure 6.1. The hydrograph (Figure 4.25) for the pre-project period generated using SOBEK 2-D overland flow model and hydrograph (Figure 4.27) for the post-project period generated from NAM rainfall runoff model are also included in Figure 6.1. As seen from this Figure, only SIS can somehow sustain during the post-project period.

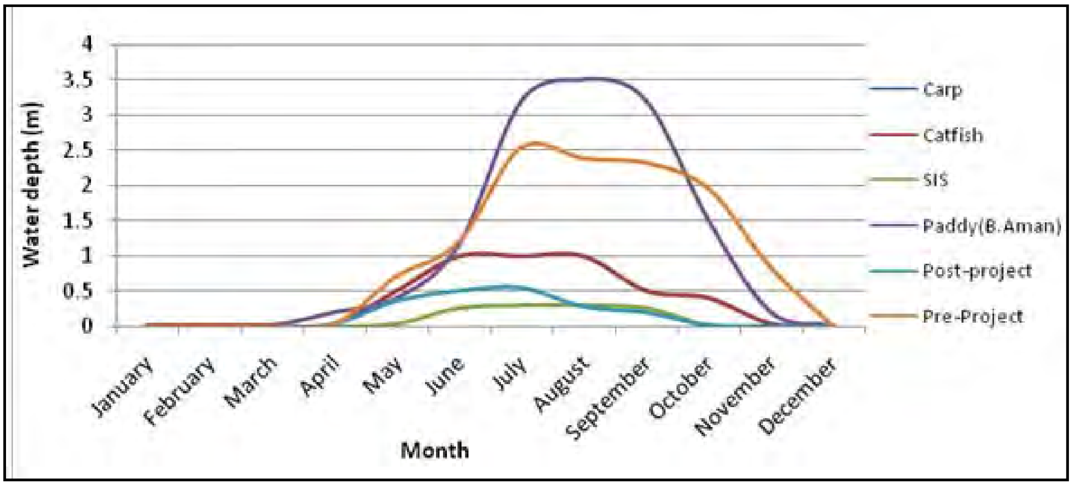

Figure 6.1 Hydrographs required for B. Aman, carp, catfish, SIS, and of pre-project and post-project periods

6.2 Application of Decision Aid Framework in the Study Area

The decision aid framework as shown in Figure 3.2 has been applied in the study area to attain a hydrograph through flood management which is ecologically and hydrologically suitable for the study-area-floodplain. The framework summarises month wise checking of water requirement of paddy and other fish species. The minimum and maximum water requirements, ie depths of water, are the range of eco-hydrological balance which is needed to be attained by a combination of flood management of structural measures and governance.

The flood management structures have been set up with a combination of embankment, canal and regulator system. The regulators have been operated and controlled through a trial and error process to attain the required hydraulic condition for the sustenance of both hydrology and ecology of the study area. In the trial the minimum water depths required for fish of three dominant species namely carp, catfish and SIS have been taken as the lower limits of water depth at the regulators. Timing of operation of regulators, *ie* when to open and when to close the gates, has been considered an important factor of trial and error process as in one hand river flow with fish spawns have been allowed to enter into the floodplain and on the other hand flooding harmful to crop has been controlled. It has been seen that closing of gates at the end of June or in very early July does not allow much fish spawns to enter into the floodplain and keeping the gates open till the very end of July causes unwanted flooding inside the floodplain.

6.2.1 Developing a hydrograph suitable for floodplain ecosystem

Data on spawning migration of fish suggest that closing gates of the regulators at the end of June or in very early July does not allow much fish spawns to enter into the floodplain. Gates need to keep open for some more days. SOBEK 2-D overland flow model has been run for two timings: keeping the gates closed between mid July and mid October, termed as Option 1, and between very early August and mid October, termed as Option 2. Figure 6.2 shows the floodplain inundation generated for Option 1.

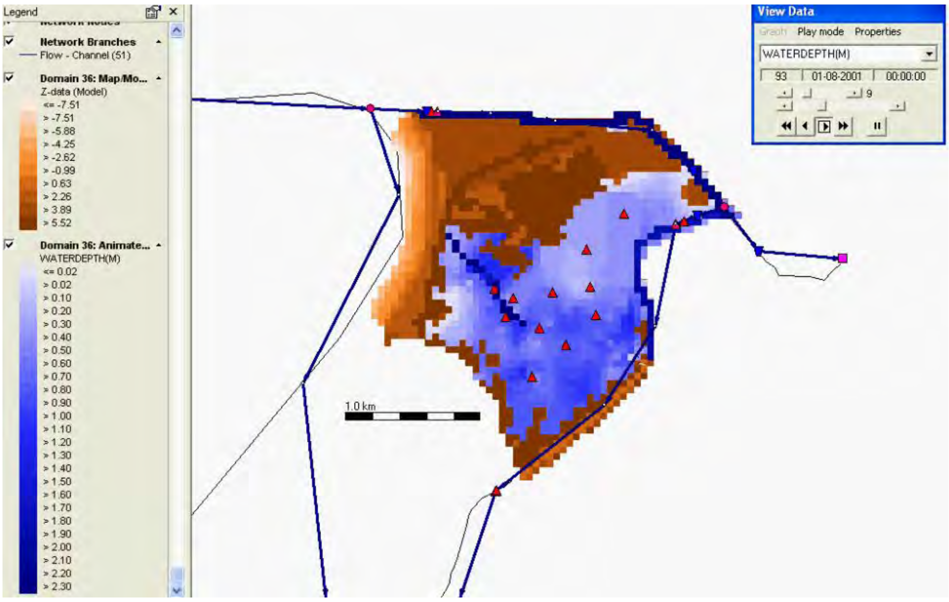

Figure 6.2 Floodplain inundation generated for an ecohydrological option

Finding out an optimum ecohydrograph

From a trial and error process, taking the minimum water depths required for carp, catfish, and SIS as the lower limit and maximum tolerable water depth for B. Aman as the upper limit, two hydrographs for the floodplain, one for Option 1 and the other for Option 2, have been generated. These two hydrographs are presented in Figure 6.3 with other hydrographs. It is seen in Figure 6.3 that both hydrographs for Option 1 and Option 2 fall within the upper and lower limits of the water depths suitable for B. Aman and fish. Therefore both are ecohydrologically suitable for the study area; but the optimum one has been chosen comparing total Aman (B. Aman and T. Aman) production in Options 1 and 2 and considering tradeoff between Aman (total) and fish.

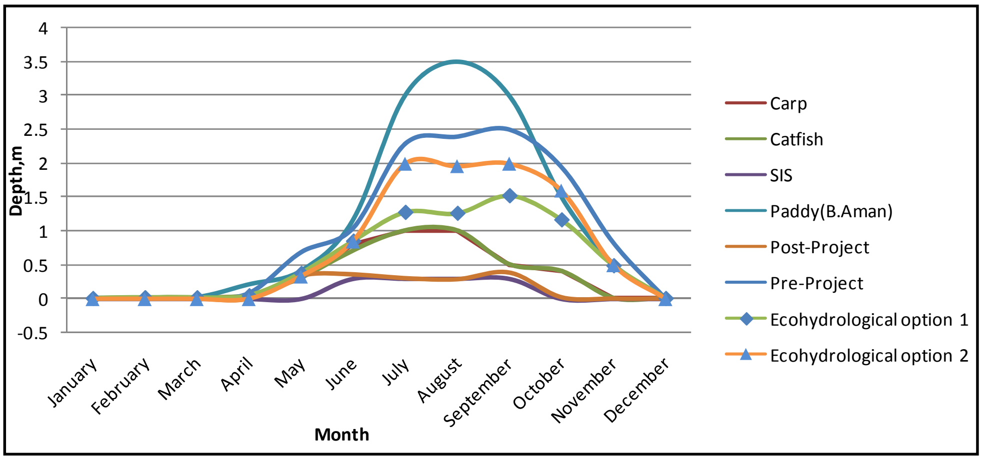

Figure 6.3 Ecohydrographs with respect to hydrographs for paddy and fish

The land types with respect to hydrographs for Option 1 and Option 2 have been prepared from SOBEK model results and are presented in Figure 6.4 with the pre- and post-project land types. Area of different land types in Option 1 and Option 2 has been estimated and is given in Table 6.1, which also includes area of land types of pre- and post-project periods.

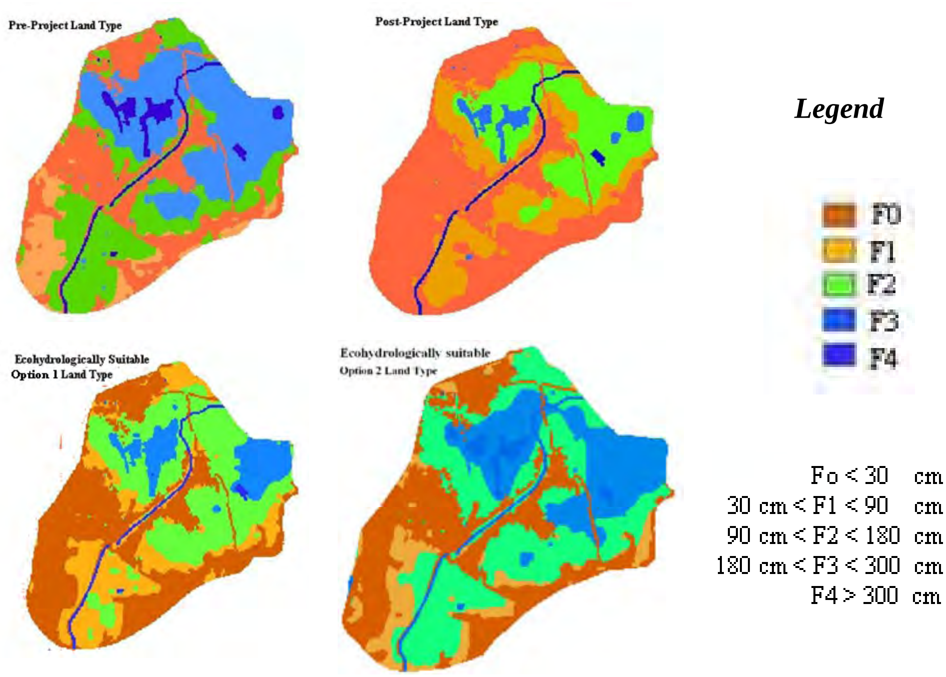

Figure 6.4 Pre-project, post-project and ecohydrologically suitable land types

Table 6.1 Land type area under different periods and options

Land Type	Area (ha)			
	Pre-project period	Post-project period	Ecohydrologically suitable option 1	Ecohydrologically suitable option 2
F0	321	566	448	378
F1	102	277	225	113
F2	314	241	338	394
F3	352	36	108	213
F4	53	22	23	44

Comparison between B. Aman and T. Aman production

From land types of F0, F1, F2, and F3, crop suitable areas for B. Aman and T. Aman in pre- and post-project periods and ecohydrologically suitable Options 1 and 2 have been calculated according to the instructions given in Soil and Land Resources Information System (SOLARIS) database of 2008 prepared from the Upazila Mritika Nirdeshika of the Soil Resource Development Institute (SRDI). These are shown in Table 6.2. The F0 and F1 lands are suitable for T. Aman. Settlement and road areas have been deducted to calculate T. Aman area of F0 land. Whole F1 and F2 lands and part of F3 land are suitable for B. Aman. Half of F3 land has been considered suitable for B. Aman as per SOLARIS database of SRDI (SRDI, 2008).

Table 6.2 Land suitable for B. Aman and T. Aman in different periods and options

Crop area	Pre-project period	Post-project period	Ecohydrologically suitable Option 1	Ecohydrologically suitable Option 2
T. Aman Area (ha)	134.68	525.8	355.88	158.96
B. Aman Area (ha)	592.42	535.9	617.2	613.7

From the Office of the Sub-District Agriculture Officer of Kashiani Sub-District, the yields of B. Aman and T. Aman have been taken as 0.9 ton/ha and 1.2 ton/ha respectively. During interview, the farmers have reported a little higher yield; but the official figures have been considered. Farmers also have reported that they lose B. Aman once in every four/five years because of no rain; hence B. Aman production has been taken as 80% for post-project period. B. Aman, T. Aman and total Aman productions are shown in Table 6.3.

Table 6.3 Production of B. Aman and T.Aman in different periods and options

	B. Aman			T. Aman			Total
	Area (ha)	Yield (ton/ha)	Production (MT)	Area (ha)	Yield (ton/ha)	Production (MT)	Aman (MT)
Pre-project period	592	0.9	533	135	1.2	162	695
Post-project period	536	0.9	386	526	1.2	631	1017
Ecohydrologically suitable Option 1	617	0.9	556	356	1.2	427	983
Ecohydrologically suitable Option 2	614	0.9	552	159	1.2	191	743

Mainly because of increase of F2 land in ecohydrologically suitable Option 1, B. Aman increases by 170 MT from post-project period. Increase of B. Aman production in ecohydrologically suitable Option 2 has been almost same. T. Aman production decreases by 204 MT in ecohydrologically suitable Option 1 because of decrease in high lands. In ecohydrologically suitable Option 2, T. Aman production has been found very low. A net loss of Aman (total) production has been estimated at 34 MT in ecohydrologically suitable Option 1 with respect to post-project period. This is about 3.34% loss while this loss is about 27% for ecohydrologically suitable Option 2. Farmers have been adapted to T. Aman production in the post-project period because of flood protection. Hence the option that suggests much reduction in T. Aman production is not acceptable to the farmers. Therefore comparing total Aman production, Option 1 has been found suitable. Again in post-project period there has been uncertainty in B. Aman production. B. Aman production depends on rainwater and, as farmers reported, there has been uncertainty in rainfall in the study area and there has been loss of B. Aman production in post-project period. But ecohydrologically suitable option will ensure flood water inside the study area; therefore farmers will be able to produce B. Aman ever year. Monsoon flooding enhances dry season crop production.

Comparison between fish and Aman production

The F2, F3 and F4 type lands are suitable habitats for fish and other aquatic biota. Table 6.1 shows that these land types comprise about 63% of the study area in pre-project period; while it reduces to only 26% in the post-project period and reaches to 41% in ecohydrologically suitable Option 1. In ecohydrologically suitable Option 2, these land types reach to 57% of the study area, which indicates a flooding situation that existed during pre-project period. The fish yield varies from land type to land type and from pre-project to post-project periods. The pre-project period fishery has been taken as open water fishery because the study area was then part of a natural river-floodplain system. Therefore fish yield of 1984 for F2, F3 and F4 lands estimated by DOF has been taken as pre-project period fish yields (Table 5.6). During post-project period fish yield has been decreased because of contraction of wetlands due to flood control intervention and modern agricultural practices such as use of indiscriminate fertilizer and pesticides. Fishery Research Survey System (FRSS) suggested a decrease fish yield for an intervened floodplain. Fish yield of 2010 estimated by DOF has been taken as the post-project period fish yield (Table 5.6). Since ecohydrologically suitable option will improve floodplain ecosystem and fish habitat; therefore fish yield will also increase. So the fish yield for ecohydrologically suitable options has been assumed as 200 kg/ha for F2 and F3 lands and 430 kg/ha for F4 land, which are between pre- and post-project values. The fish production has been estimated and is shown in Table 6.4.

Table 6.4 Fish production in different periods and options

Habitat type	Fish production (MT)			
	Pre-project period	Post-project period	Ecohydrologically suitable Option 1	Ecohydrologically suitable Option 2
F2	76.8	38.5	67.6	78.8
F3	85.9	5.9	21.6	42.6
F4	23.8	8.9	10.0	18.9
Total	186.5	53.3	99.2	140.3

Fish production has decreased significantly in post-project period; but increases considerably in Option 1 and Option 2. The Option 2 looks preferable to Option 1 with regard to fish production. On the other hand Option 2 brings huge area under flooding, which reduces Aman area and production. Fish production in Option 1 becomes almost double than that of pre-project production; while there has been a net loss of only 3.34% Aman production. Though fish production has been more in Option 2 than Option 1, there has been 27% reduction in Aman production in Option 2. Aman and fish productions are shown together in Figure 6.5. Taking into account the existing practice of Aman cultivation, the farmers have been adapted to, and significant increase in fish production, ecohydrologically suitable Option 1 has been taken as the optimum ecohydrological option.

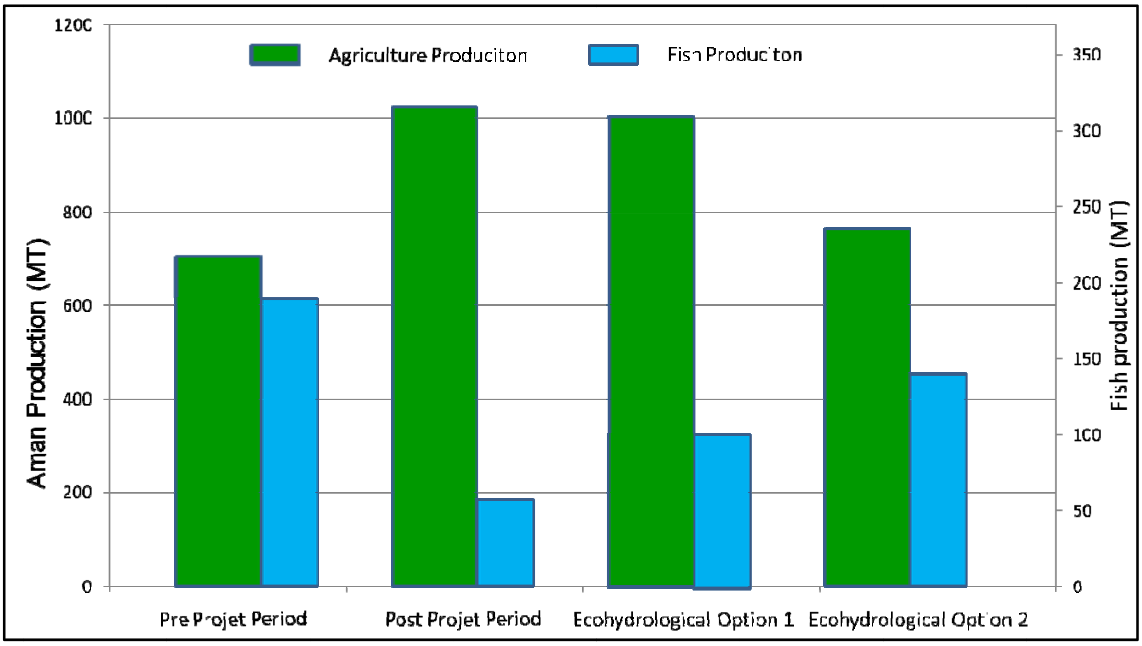

Figure 6.5 Aman and fish productions in different periods and options

6.2.2 Assessment of impact with respect to the optimum ecohydrograph

The values of hydrological and ecological indicators have been calculated with respect to the optimum ecohydrograph. These values are then compared with the pre- and post-project periods' values to assess the changes.

6.2.2.1 Impact on hydrology

The hydrological indicators under five functions of the floodplain have been analysed. The relative values of the indicators suggest the condition of the floodplain at pre and post-project periods and optimum ecohydrograph. The values of various hydrological indicators are shown in Table 6.5 and the indicator-wise impacts have been described in the following sections:

Table 6.5 Hydrological indicators at different options

Functions	Indicator		Unit	Pre-Project period	Post-Project period	Optimum ecohydro-graph option
Regulation	Maximum average depth in floodplain		m	2.54	0.55	1.5
	Flooded area		%	63	26	42
Connectivity	Conveyance characteristics	Bhatiapara Khal	sq m	342	0	342
		Internal khal	sq m	273	240	273
	Duration of flow in connecting river/khal with beel		day	175	0	148
Regeneration	Recharge		Mm^3	4.84	4.16	4.26
Floodplain sustenance	Maximum flow in floodplain		$m^3/s/m$	0.28	0	0.12
Biodiversity habitat	Beel area (F3+F4)		ha	404	59	131

Regulation function

The first hydrological function is the regulation of flow in the floodplain. The indicators under this function are the maximum average depth of water in floodplain and flooded area. The maximum average depth at pre-project period is estimated from the modeled results at 2.5 m, while at optimum ecologically suitable option it is estimated at 1.5 m. At post-project period, where only rainfall is the source of water in the project area the water depth is estimated at 0.38 m from rainfall runoff model. The flooded area has decreased drastically by 37% in post-project period and increased in optimum ecohydrological option by 16 % than the post-project period. Figure 6.6 shows the comparison of the indicators of regulatory function.

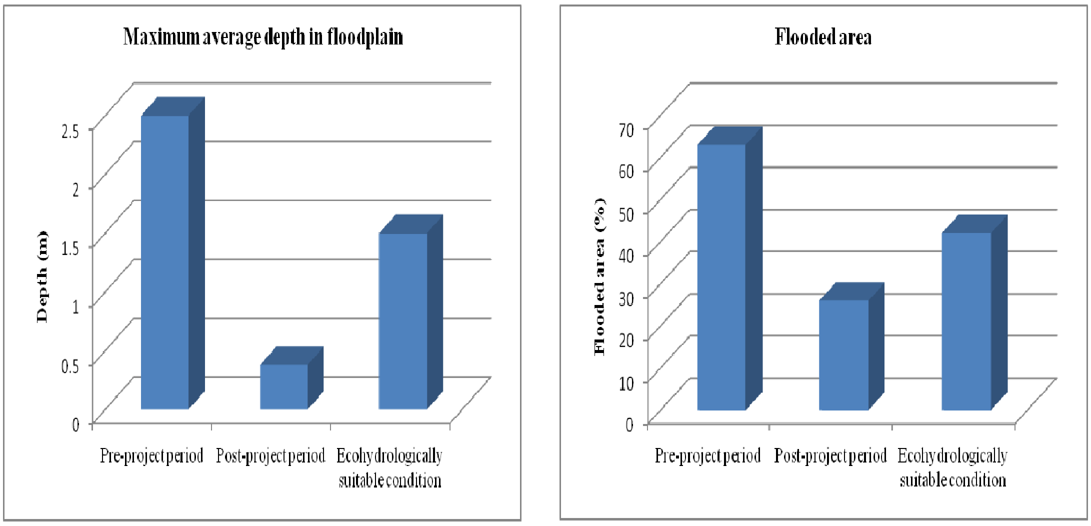

Figure 6.6 Regulatory hydrological function at different periods and option

Connectivity function

Conveyance characteristics and duration of flow connecting river, channel, floodplain and wetlands are the indicators of the connectivity function. The conveyances characteristics have been measured by the cross-section area of the channel. As in post-project period after 1990 there is no flow in the Bhatiapara Khal hence it has no conveyance capacity. Besides, the channel and the canal need re-excavation to regain the previous conveyance of 342 m^2. For the internal canal, the conveyance has been reduced due to siltation and the canal needs excavation to gain its previous conveyance capacity. There is no connectivity of the channel and canal with the floodplain at post-project period. At optimum ecohydrological option connectivity is estimated at 148 days though it is less than the connectivity of the pre-project period of 175 days. A comparison of conveyance characteristics of the river-floodplain system of the study area is shown in Figure 6.7.

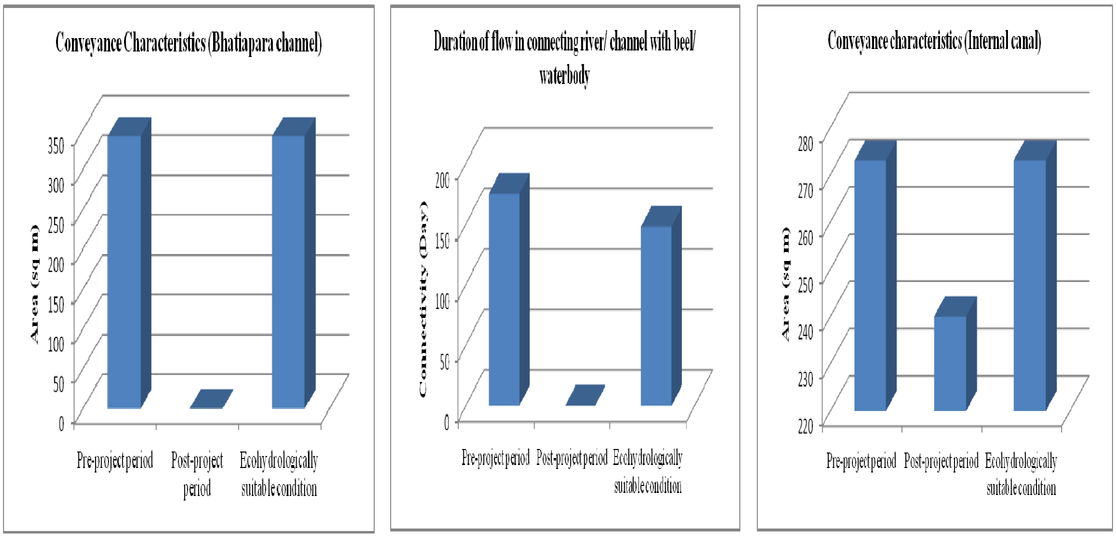

Figure 6.7 Comparison of connectivity functions under different periods and option

Recharge function

Recharge has been taken as the indicator for the regeneration function. Two types of recharge have been considered. Recharge from rainfall and recharge from flooding. Due to intervention recharge has been hindered as there is no flooding from the river to the study area. The only source of recharge is rainfall. Recharges have been estimated for pre-project period and ecohydrologically suitable option from both flooding and rainfall. This is shown in Figure 6.8.

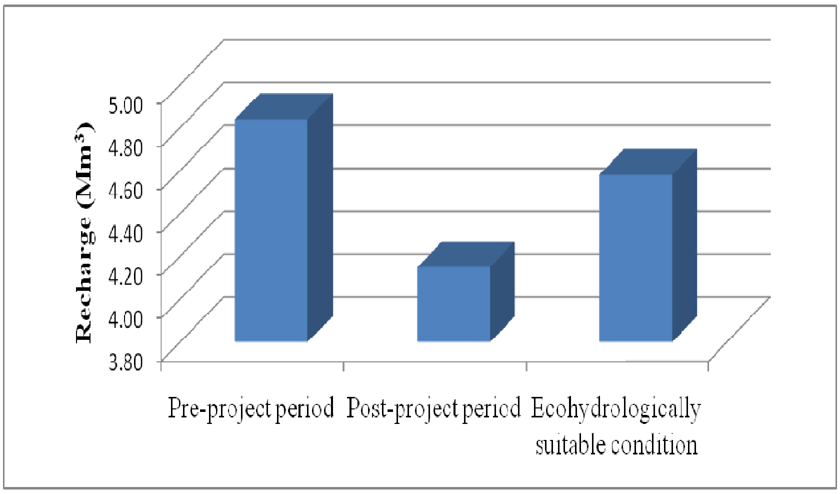

Figure 6.8 Recharge under different periods and option

Recharge is much higher in pre-project period as the project area used to be flooded regularly both from river flow and rainfall. Recharge has been reduced in post-project option as there is no flooding inside the project area because of its disconnection from the river. But in ecohydrologically suitable option estimated recharge is found higher than the post-project period because there will be periodic flooding if ecologically suitable option is exercised.

Flow function

For the sustenance of floodplain maximum average flow of 0.28 m^3/s/m has been taken as the indicator. The indicator value is the maximum in pre-project period and optimum at optimum ecohydrological option. There is no flow in the floodplain during post-project period.

Biodiversity habitat function

Amount of wetland area, *ie* biodiversity habitat, indicates biodiversity of a floodplain or wetlands. Wetland area is estimated at 404 ha at pre-project period and only 59 ha at post-project period. This indicates a huge reduction in biodiversity, and a dominance of species. At ecohydrologically suitable option wetland is estimated at 131 ha, which indicates a return to more biodiversity and less species dominance than the post-project period. Both flow function and biodiversity function are shown in Figure 6.9.

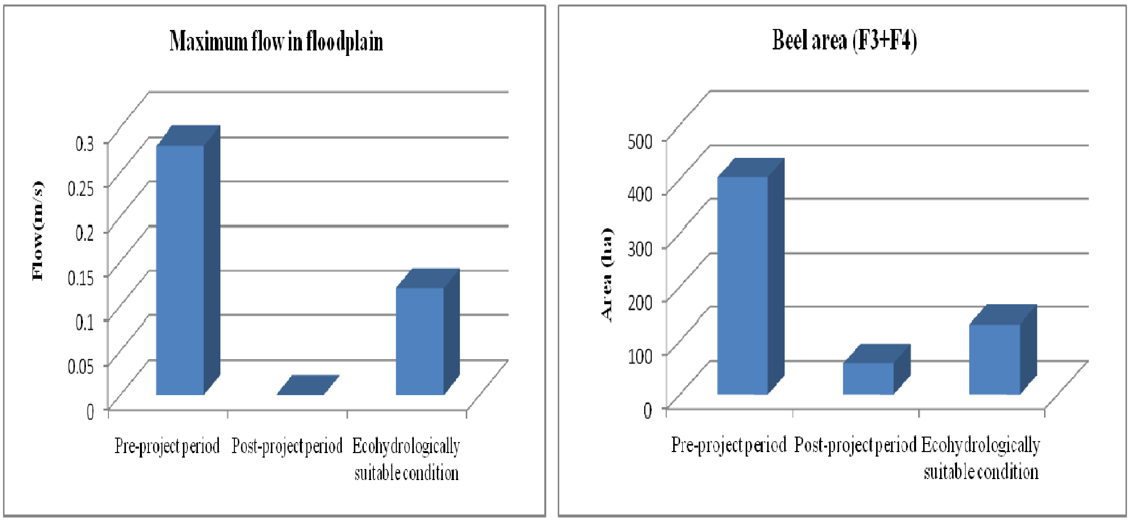

Figure 6.9 Flow and biodiversity comparison under different option

6.2.2.2 Impact on ecology

The values of the ecological indicators give a situation of the ecosystem of the floodplain. The ecological functions of the floodplain can be understood from the values of the indicators and their comparison under different periods. The ecological function, indicator and their values in pre-project, post-project periods and ecohydrologically suitable option are shown in Table 6.6.

Table 6.6 Ecological functions and indicators in different periods and option

Function	Indicator	Duration	Unit	Pre-project period	Post-project period	Optimum ecohydro-graph option
Fauna Habitat maintenance	Area (F2+F3+F4)		ha	720	300	470
	Max average depth	April to September	m	2.54	0.55	1.5
	Max average velocity	April to September	m/s	0.2	0	0.1
	Seasonality/ connectivity	Annual	day	175	0	148
	Channel condition	April to September	length (km)	9.5	5.5	9.5
Fish migration support	Migration pattern	April to September		Long + Lateral	Lateral only	Long + Lateral
	Spawning migration	April to September	month	5	0	3
	Hatchling migration	April to September	month	5	0	2
Conserve Biodiversity	Species variation	Annual	Indicative species (no)	48	19	(+/-) 35
	Species dominance	Annual	Individual Dominance	High Low	Low High	Moderate Moderate
Fish Production	Yield	Annual	MT	186	53	100

Faunal habitat condition

Land-types of F2, F3 and F4 have been considered as fish habitat. Fish habiat will improve at the proposed optimum ecohydrological condition. From the analysis, it has been found that the fish habitat has reduced from 720 hectare in pre-project period to 300 hectare in post-project period, which has been increased to 470 ha at ecohydrologically suitable condition. These are shown in Table 6.6 and Figure 6.10 respectively.

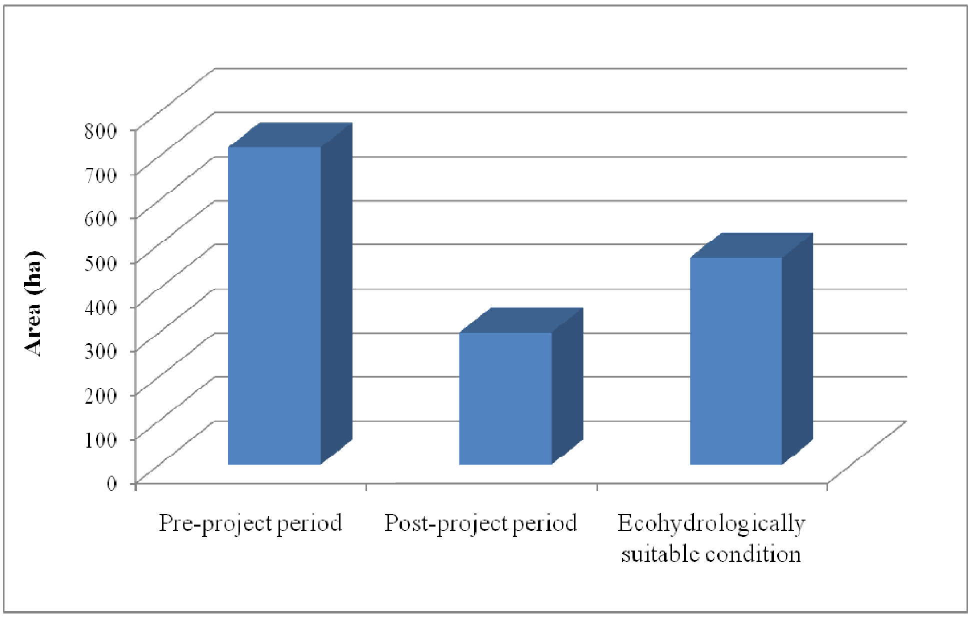

Figure 6.10 Faunal habitat area (F2+F3+F4) under different periods and option

Faunal migration and channel connectivity

At ecohydrologically suitable option faunal migration and channel connectivity have improved due to increase in channel length, changing in fish migration pattern from lateral to both lateral and longitudinal migrations, increasing the duration of spawning and hatchling migration time. Channel length that was reduced from 9.5 km in pre-project period to 5.5 km in post-project period has regained to its pre-project period of 9.5 km while connectivity of the channels has improved up to about 150 days at ecohydrologically suitable condition from almost zero days of post-project period. On the other hand, spawning migration has been extended up to 3 months at ecohydrologically suitable option whereas it was reduced from 5 months at pre-project period to nearly zero months at post-project period. The seasonality/connectivity, channel condition, spawning and hatchling migrations at different periods and option are shown in Figures 6.11-6.14.

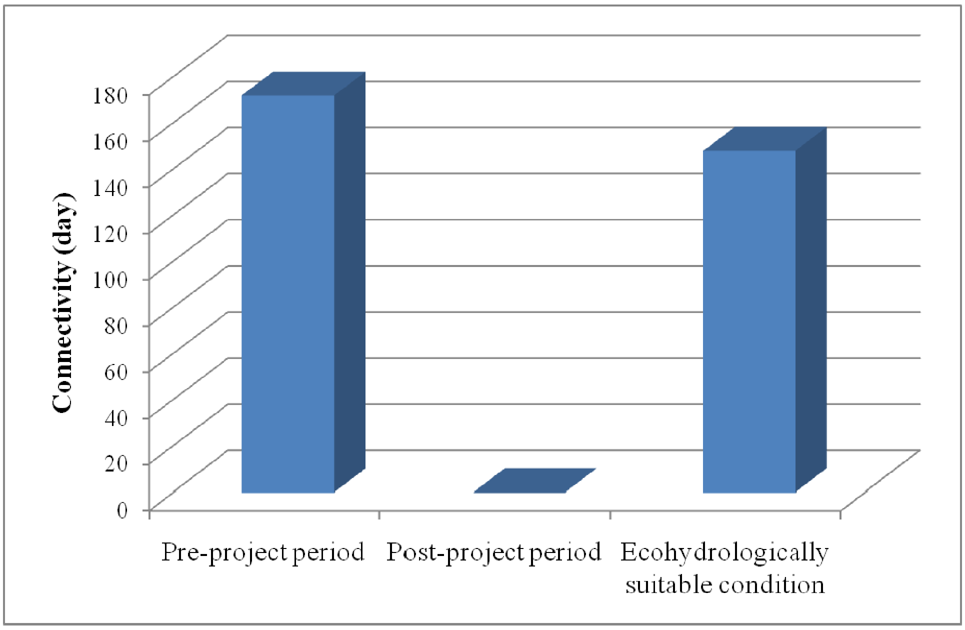

Figure 6.11 Channel seasonality/connectivity

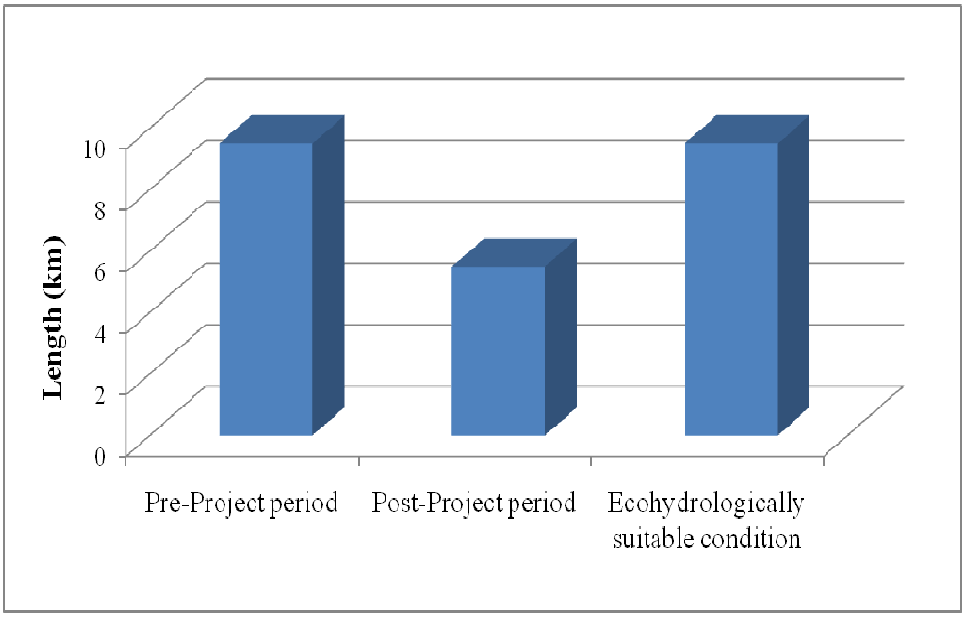

Figure 6.12 Channel condition

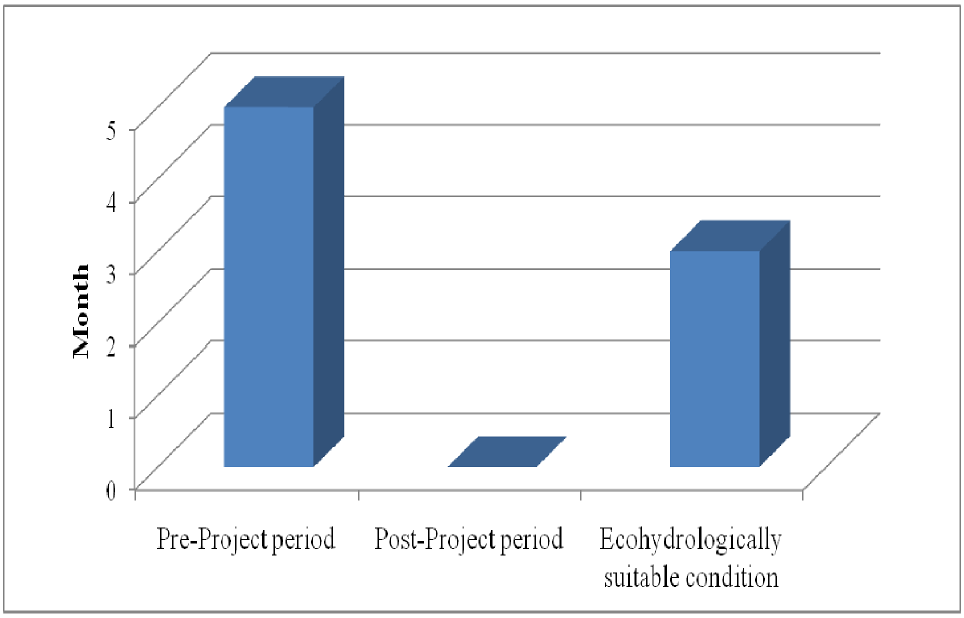

Figure 6.13 Spawning migration

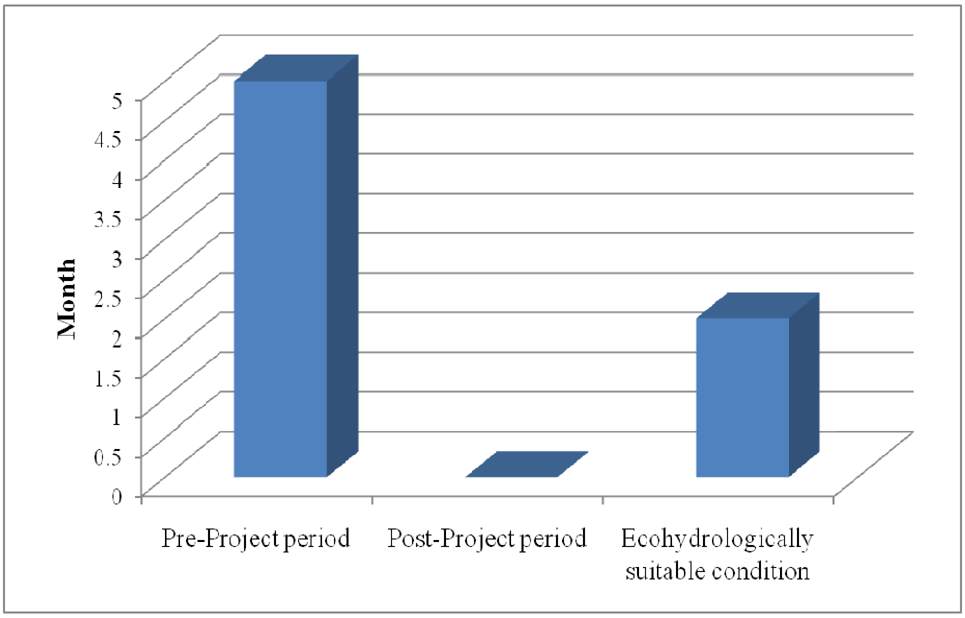

Figure 6.14 Hatching migration

Fisheries biodiversity

Taxa_S: Total 19 numbers of fish species was counted during field sampling in the study area which was almost 50% below the species count (35 numbers) in local market. It can be stated that if proposed ecohydrologically suitable condition can be ensured, which will reestablish the connectivity and flow between the study area and the surrounding water system, the number of fish species will be increased in the study area up to 35 numbers which are highly available in and around the floodplain of the study area. On the other hand, if the seasonality, channel length, and migration time at different stages of fish lifecycle can be improved with the implementation of the proposed ecohydrologically suitable option, species abundance will be increased, degraded health of the ecosystem will be improved and species dominancy will be reduced as well.

6.3 Eco-Friendly Flood Management Infrastructure for the Study Area

Here eco-friendly flood management infrastructure is a flood management system that allows flood flow in the controlled area suitable for maintenance of the ecosystem. It refers to the hydraulic condition of the flow *eg* depth, speed, duration, frequency, advance and retreat and timing of flow that is friendly to the ecological community of the controlled floodplain. It also refers to the water governance that ensures the operation of the flood controlling structures to achieve an ecohydrograph for the controlled area that is appropriate for both paddy and biotic community of the floodplain. Only flood flow from the river to its floodplain will not help the ecosystem of the floodplain much; rather flow variability, that is flow fluctuation and periodic wetting and drying, needs to be maintained in the floodplain according to the requirement of the lifecycle of the biotic community of the floodplain. The eco-friendly flood management may be attained through various combinations of flood control infrastructure. The main emphasis of this eco-friendly flood management is the consideration of the minimum requirement of the floodplain fisheries and wet season agriculture. Besides it will also control the overflow to the floodplain flooding. This can be achieved in different ways. For an existing flood management project, the infrastructures such as the embankment, sluices, and canal system may be rehabilitated and the operation may be conducted according to the guidelines prepared for ecohydrological flood management. Reengineering, *ie* removing the embankment or constructing more controlling structures or doing both, of an existing flood management project will not be feasible for people have already settled in and changed the land-use. Again for an existing flood management project where there are public cuts for flood attenuation, more controlling structures may be constructed and the whole project may be operated as per the ecohydrological need of the controlled area. For a new flood management project, the decision aid developed under this research may be applied to determine the ecohydrological need of the floodplain and the project may be operated and maintained accordingly.

For the study area, water governance, *ie* judicious operation of the regulators, has been suggested to attain eco-friendly flood management. It is suggested to reopen the Bhatiapara Channel which was closed by constructing a road over it and to operate the sluices as per the need of the ecohydrology of the project area. This may be done through several steps and arrangement. There is a flood protection embankment around the study area. Out of four regulators, three are located on the embankment and one is on the internal canal inside the study area (Figures 4.1 and 6.15). Theses regulators are out of service. The Bhatiapara Channel is closed, making the study area completely disconnected from the Madhumati River; and part of the Channel inside the study area is silted up. The road junction at the Bhatiapara Channel should be cut and opened to revive the channel connection with the study area and its surrounding. However, a bridge at this point should be constructed to maintain road communication. The Bhatiapara Channel and the internal canal need re-excavation. The regulator R1 at the off-take of Bhatiapara Channel and the Madhumati River should be reconstructed and other three regulators R2, R3 and R4 should be repaired to function properly. Now the regulators in and around the study area may be controlled following the operation rules suggested in Section 6.4.2 to allow flood water inside the study-area-floodplain to achieve the ecohydrograph developed for the study area under this research. To maintain social harmony, regulators R1 and R2 need to be controlled by the people of Budpasha Mauza and regulator R4 is to be controlled by the people of Charbhatpara

Mauza. Regulator R3, as it is situated at the border of two mouzas, should be controlled by the people of Bhudpasha and Char Bhatpara Mauzas as per requirement.

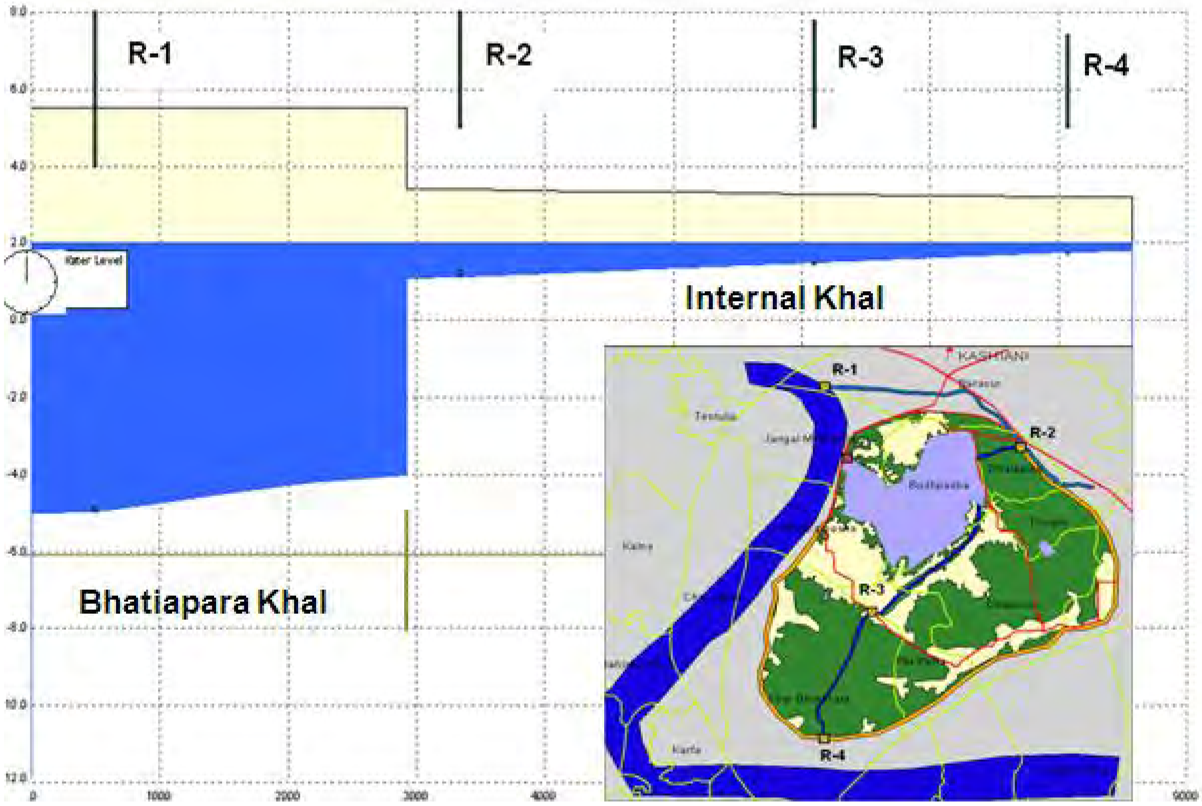

Figure 6.15 Locations of canals and regulators

6.4 Suggestions for Improvement of Existing Flood Management System

Presently the study area is fully closed and disconnected from the external sources of water particularly from the Madhumati River, the only source of river water. The Bhatiapara Channel lost connectivity with the study area when the bridge over the Channel along the Bhatiapara-Shankarpasha road was removed and road embankment was constructed in its place. The Bhatiapara Channel inside and outside the study area is silted up. Internal canals are also silted up. The regulators are out of service. All walks of life inside the project area, *ie* farmer, fisherman, etc, have demanded reconnection of the Bhatiapara Channel between the project area and the river.

Improvement of the existing flood management system refers both rehabilitation of the physical components of the existing Purulia Char Bhatpara Flood Control, Drainage and

Irrigation Project and application of the decision aid framework, developed under this research, in the project area. Application of the decision aid framework will allow flood flow suitable for both paddy and ecological community of the project area.

6.4.1 Required change in existing flood management interventions

Change in the existing flood management interventions has been suggested in the eco-friendly flood management option developed under this research.

The following changes in the existing flood management intervention have been suggested to achieve an eco-friendly flood management system:

- The Bhatiapara Channel at the junction of the Bhatiapara-Shankarpasha road and the channel should be opened to establish a connection between the river Madhumati and the project area. However a bridge at this junction may be constructed to maintain communication.

- The Bhatiapara Channel and the internal canal from Dholsree to Charbhatpara should be re-excavated to increase the conveyance capacity. This will help improve flow connectivity of the canal and the floodplain inside the project area.

- The regulator at Bhatiapara should be reconstructed and the regulator at Dhlosree should be improved and maintained.

- The regulators at Budpasha and Charbhatpara are needed to be repaired.

- The decision aid framework for consideration of ecohydrological criteria in flood management developed under this research should be applied in the project area as per suggested operation rules given in Section 6.4.2 to reestablish the flood flow suitable for both paddy and fish of the project area.

The whole study area has been considered as a controlled flooding system of embankment and regulators where only regulators will allow flood flow in the project area from the river Madhumati.

6.4.2 Operation rules for flow control structures

Regulation of flow at the flood control structures is the most important part of flood management to allow optimum flood flow suitable for both paddy and aquatic biota of the flood controlled area. Traditional flood management allows water in the controlled area to fulfill the need of crop growth only. From this research it is found that flood flow in terms of magnitude and timing may be allowed to enter into the project area which is very much crucial for the sustenance of the aquatic biota but not detrimental to paddy. A little modification in the operation rules of flow controlling structures will help to attain a hydrological condition that is suitable for both paddy and ecological community inside the project-area-floodplain.

The regulator R1 at the off-take of Bhatiapara Channel and R4 at the outfall of the internal canal on the Madhumati River may be kept open up to middle of July. This will allow a flood pulse between the river and the floodplain because Madhumati River is a tidal river. Then R1 needs to be kept close till mid October. This will allow a maximum water depth of 1.5 m in the F3 and F4 type land and inundate about 41 % of the study area during this period. This is suitable for the ecosystem of the study area. After mid October regulator R1 and R4 may be reopened. This will allow out-migration of juvenile and adults to the Madhumati River. Then between mid October and mid July the closed floodplain will be a partially controlled floodplain with ecohydrological conditions suitable for both paddy and ecological community. This will allow exchanges of nutrient and organic matter and sediment and fish larvae/egg between the river and the project area. The regulator R4 at the outlet of the internal canal at Charbhapara needs to be closed between November and March to store water inside the southern part of the project area. The other regulators, R2 and R3, need to be operated in harmony with R1 and R4 to allow water spread inside the project area as per the land elevation. An operation schedule for regulators has been suggested and is given in Table 6.7. Regulator operation at optimum ecohydrograph option is shown in Figure 6.16. Long-profile of Bhatiapara channel and internal canal with closing and opening operation mode of regulators R1, R2, R3 and R4 are shown in Figures 6.17-6.19.

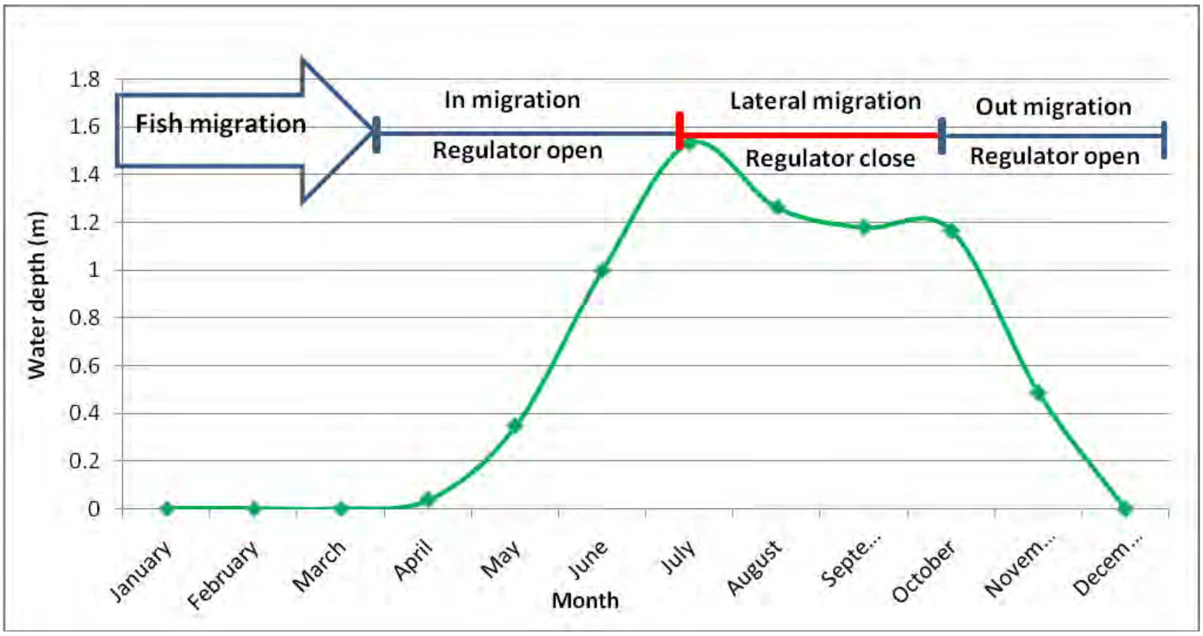

Figure 6.16 Regulator operation at optimum ecohydrograph option

Table 6.7 Operation schedule for regulators in the study area

Duration	Requirement	Regulation decisions	Recommended water level (WL) at regulators
Up to mid July	Allow minimum water depth of 1 meter in the floodplain for in-migration.	Keep all regulators open.	Up to WL< 4.1 m at R1 and WL<3.3 m at R4
Mid July to mid October	Control flooding with time and water level (if more depth envisaged for specific purpose in the floodplain).	Keep all regulators close. However open for short time in August to allow Rui spawns enter into the floodplain.	When WL> 4.1 m at R1 and WL > 3.3m at R4
Mid October to November	Allow water outflow up to 0.5 m depth at floodplain for out-migration.	All regulators are reopened.	Up to WL< 4.1 m at R1 and WL<3.3 m at R4
November to March	Conserve water for multiple uses.	Keep R1 open but control R2, R3, R4 for water storage.	Close R2, R3, R4 to maintain water depth up to 0.5 m in the floodplain.

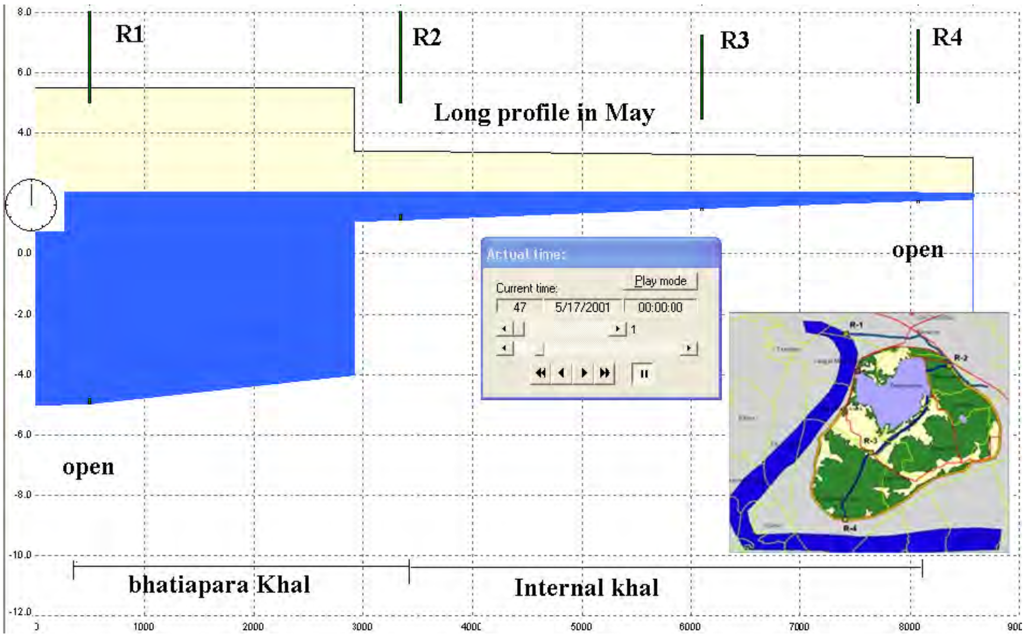

Figure 6.17 Long profile of canal with regulators in May

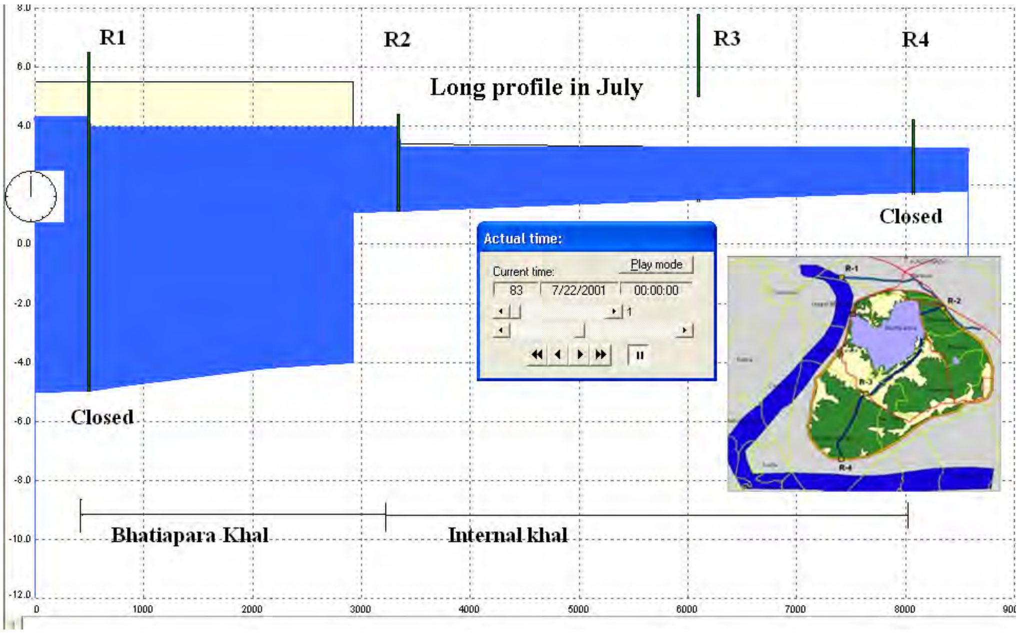

Figure 6.18 Regulators operation status in mid July

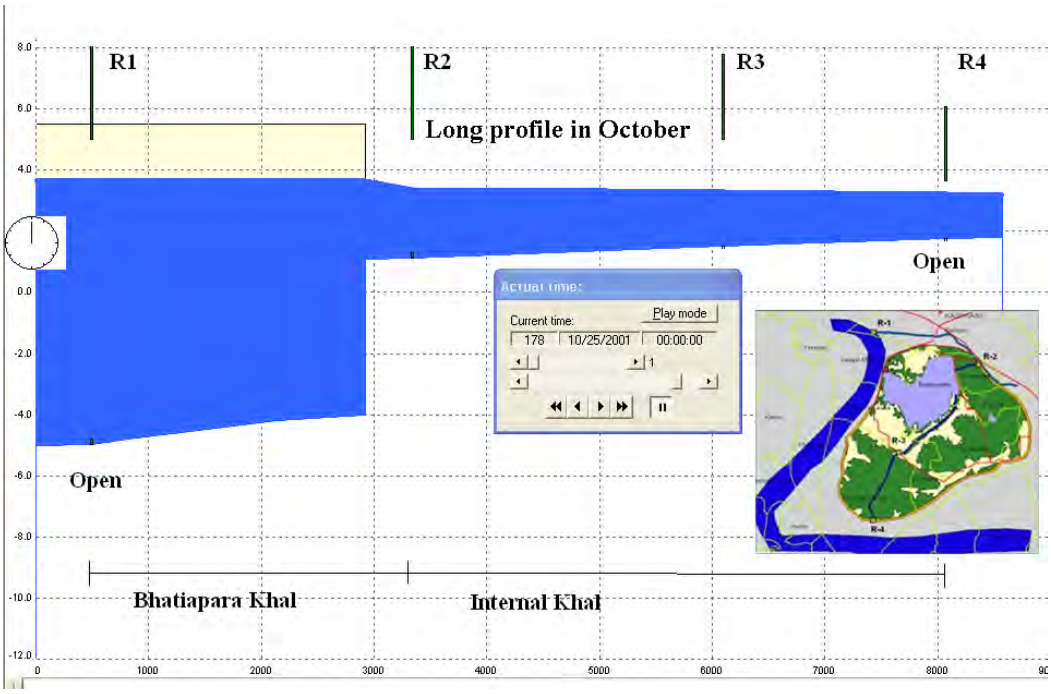

Figure 6.19 Regulators status in mid October

A general operation schedule for regulators and a floodplain ecohydrological calendar for regulator operation have been suggested in Tables 6.8 and 6.9.

Table 6.8 General operation schedule for regulators

Duration	Requirement	Decision
Up to July	Allow minimum water depth of 1 meter in floodplains for in migration. This can be done by keeping the gates open until water levels at regulator point corresponding to the required water depths in the floodplain is attained.	Keep regulator open.
July-October	Control flooding with time and water level at regulator point with respect to water depth in the floodplain.	Keep regulator close. Open for short time in August to allow fish or spawns of fish that spawn late (*eg Rui*) enter into the floodplain.
October-November	Keep minimum water depth of 0.5 m in the floodplain. Keep gates open for out migration until water levels at regulator point corresponding to 0.5 m depth of water in the floodplain is attained.	Keep regulator open. Keep internal regulators open or close to balance water depths inside the compartments.
November-March	Conserve water for multiple purpose uses.	Keep regulator close.

Table 6.9 Generalised floodplain ecohydrological calendar for regulator operation

<table>
<tr><th></th><th>April-May</th><th>May-June</th><th>June-July</th><th>July-August</th><th>August-September</th><th>September-October</th><th>October-November</th></tr>
<tr><td>In-migration</td><td colspan="3">Open</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lateral migration/ spreading / feeding / rearing</td><td></td><td></td><td></td><td colspan="3">Close/Open</td><td></td></tr>
<tr><td>Out-migration</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Open</td></tr>
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Chapter 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

Consideration of ecohydrological criteria in flood management can restore or preserve the ecosystem of a deltaic floodplain. This study has developed an ecohydrograph and a decision aid framework for determination of flood management option and flow regulation which consider both ecological and hydrological criteria in flood management intervention in deltaic floodplain. The study introduces a term 'ecohydrograph' that combines hydrological requirement of the floodplain ecological community with respect to seasonality; implementation of which will help sustain the floodplain ecosystem. A simple decision aid framework has been developed that gives, as an output, an eco-friendly flood management infrastructure and operation rules for flow control structures corresponding to the ecohydrograph. Implementation of the ecohydrograph will reestablish a hydrological environment in a modified or damaged floodplain, which will support living system of the biotic community of the floodplain.

In this study three objectives have been achieved. Flood flow characteristics that are vital for ecosystem sustenance in a deltaic floodplain have been determined. An ecohydrological relationship has been developed for prediction of impact of change in flood flow regime on hydrology and ecological resources of a floodplain. A decision aid framework combining hydrology and ecology of a river-floodplain system has been developed for consideration of ecohydrological criteria for flood management in deltaic floodplain and applied in a modified floodplain.

Hydrological indicators with respect to functions of the floodplain ecosystem have been developed. These indicators have been selected in connection with five functions of hydrology to floodplain ecosystem. The functions are regulations of flow, connectivity of river with the floodplain, regeneration of water, environmental sustenance, and biodiversity habitat maintenance of floodplain. The regulatory function refers to the capacity of the floodplain to alleviate river floods during the monsoon season through storage of peak river discharge in the floodplain. During the dry season a main function of the floodplain is to retain and supply water. This relates to the capacity of the system to store water during the monsoon and to make this water available during the dry period. Conveyance characteristics of the channel and duration of flow between the river and its floodplain refers to the connectivity function. Maximum average flow in the floodplain indicates environmental sustenance and the amount of wetland area in the floodplain indicates the biodiversity. Water recharge, a very important function, refers to the regeneration capacity of the floodplain.

Ecological indicators have been selected with reference to its functions and hydrological indicators. The functions are floral and faunal habitats, migration support, biodiversity, and the production and productivity of floodplain. Extent of flood area during wet season is vital for the floodplain flora including crops and the aquatic fauna especially fish and shrimp. Least amount of floodplain habitat is the pre-requisite for smoothing the ecological viability like regeneration and productivity of floodplain crops and fisheries. Average flooding area, depths variability, water flow condition and the seasonality of the connecting channels between floodplain and river are the main indicators considered for analysis of habitat condition in reference to specific floodplain crops and fishes. Migration support for the fish-fauna is prime important for their life cycle completion. Fish and other aquatic fauna have the high dependency on water flow for their spawning migration as well as for lateral migration to spread over the floodplain searching for food. These processes are very important for production and productivity. Biodiversity of the floodplain and river is the basic component for ultimate sustainability. The numbers of species and their evenness and dominances are the function of floodplain biodiversity indicator.

Based on the range of the values of the indicators, a relationship between hydrology and ecology has been developed in the form of floodplain hydrographs, and a band of the value of water depths has been identified which are suitable for both floodplain fauna and flora. An optimum hydrograph *ie* ecohydrograph within the band of values has been determined using a 2-D overland flow hydrodynamic model. The flow regulation corresponding to the ecohydrograph is the decision for eco-friendly flood management.

The decision aid framework has been applied on a flood control, drainage and irrigation (FCDI) project implemented by the Bangladesh Water Development Board in Purulia-Char Bhatpara in Kashiani Upazila of Gopalgonj District since 1983. Hydrologic, topographic, land-use and ecological data have been obtained from different agencies and collected through field survey. On the basis of biological requirement mainly behavior, migration, reproduction and growth, three ideal groups of fish *ie* carp fish, catfish and small indigenous species (SIS), and one floodplain crop *ie* Broadcast Aman paddy, presently in practice in the study area, have been selected and their water requirement with respect to time and duration have been determined. The pre- and post-project values of the indicators have been determined and the impact of flood management at pre- and post-project assessed.

Considering the requirement of water depths for paddy and fish, two hydrographs of the floodplain of the study area—one for Option 1 meaning keeping the gates close between mid July and mid October, and the other for Option 2 meaning keeping the gates close between very early August and mid October—have been generated using SOBEK model. Both hydrographs have been found ecohydrologically suitable for the study area because they fall within the ranges of water depths required for paddy and fish (Figure 6.3). Ecohydrograph for Option 1 has been chosen as the optimum ecohydrograph for the study area considering the tradeoff between Aman and fish production. Following the flood management project in the study area, farmers have been adapted to Aman crop production. Therefore Aman crop production has been preferred to fish production. Nevertheless fish production in Option 1 has been found much more than post-project period production. The values of indicators at optimum ecohydrograph (Option 1) have also been assessed. Comparing these values with pre- and post-project periods and optimum ecohydrograph option, it has been found that if the flood management corresponding to the optimum ecohydrograph is implemented then values of all indicators are improved.

The connectivity between the river and the study-area-floodplain, perennial water area, and average water depth have been increased in the optimum ecohydrograph option. Fish habitat of 719 ha in the pre-project period decreases to 299 ha in the post-project period while increases to 469 ha in the optimum ecohydrograph option. It is found that the fish production almost doubles from 53.3 MT in the post-project period to 99.2 MT in the optimum ecohydrograph option (Table 6.4), whereas, there is a net reduction of only 3.34% Aman production in the ecohydrograph option from the present Aman production. The biodiversity which was reduced to 19 in the post-project period from 48 in the pre-project period may reach up to 35 in the ecohydrograph option. Species dominance which was found ‘low’ in the pre-project period and ‘high’ in the post-project period has been improved to ‘moderate’ in the ecohydrograph option.

Improvement of and required change in existing flood management interventions have been suggested. Simple operation rules for flow controlling structures have also been suggested; compliance of which will help maintain the ecosystem of the floodplain within the intervened area. All walks of people of the study area want flood flow restoration to fulfill their household and agricultural needs and to see fish abundance again in their floodplain.

This ecohydrograph and decision aid framework would enable ecosystem approach of management of natural resources particularly water and aquatic biological resources.

7.2 Recommendations

7.2.1 Based on the study

Ecohydrological decision aid framework may be used in completed flood management projects and in planning and designing new flood management interventions. BWDB has completed more than 600 FCDI projects all over the country since mid sixties and the Local Government Engineering Department has also completed hundreds of small scale water management projects. These two organisations have been planning to implement many new flood management projects. Application of the ecohydrological decision aid framework in the completed projects would improve the hydrological and ecological environment of the projects and increase biological production in the project floodplain without hampering crop production.

7.2.2 For further research

The ecohydrological relationship and the decision aid framework have been applied in a tidal floodplain, though tide variation is low. Future research should include non-tidal floodplains and coastal floodplains as well. This ecohydrological decision aid is an integrated tool that takes care of the ecological and hydrological requirement of the river-floodplain ecosystem together. Existing guidelines for environmental impact assessment of flood control, drainage and irrigation projects lack this integrated approach of ecohydrology. Inclusion of ecohydrological approach in environmental impact assessment of FCDI projects may be examined.

REFERENCES

Agüero, M., Huq, S., Rahman, A. K. A. and Ahmed, M., (1989) *Inland fisheries management in Bangladesh*. Department of Fisheries, Dhaka, Bangladesh; Bangladesh Centre for Advanced Studies, Dhaka, Bangladesh; and International Center for Living Aquatic Resources Management, Manila, The Philippines.

BBS (2001) *Population Census 2001 Preliminary Report*. Bangladesh Bureau of Statistics, Government of Bangladesh, Dhaka.

BCAS & CDI (2006) *Impact of development intervention on wet lands, its resources and livelihoods of people in Chamba beel.* Bangladesh Center for Advanced Studies and Caritash Development Institution.

Bayley, P. B., (1995) “Understanding large river-floodplain ecosystems.” *BioScience* 45: 153-158.

Benke, A. C., Karr, J. R. and Allan, J. D., (2000) “River conservation in the United Stated and Canada.” In P. J. Boon, B. R. Davis, and G. E. Petts (eds.), *Global perspective on river conservation: Science, policy and practice*, pp. 3-40, John Wiley and Sons, Chichester, England.

Billah, A. H. M. M., (2003) *Green Accounting: Tropical Experience*. Dhaka: Palok Publishers.

Boyd, C. E., (1982) “Water quality management for pond fish culture”, *Elsevier,* UK, pp. 318.

BRAC (2008) *A Situation Analysis of Ecosystem Services and Poverty Linkages in Bangladesh.* Bangladesh Rural Advancement Committee, Bangladesh.

Brammer, H., Antoine, J., Kassam, A. H. and van Velthuizen, H. T., (1988) *Report 2: Agro-ecological Regions of Bangladesh,* Land Resources Appraisal of Bangladesh for agricultural Development, Report (BGD/81/035) prepared for the Government of Bangladesh by UNDP-FAO, Dhaka.

Brammer, H., (2002) *Land Use and Land Use Planning in Bangladesh*, UPL, Dhaka.

Bunn, S. E. and Arthington, A. H., (2002) "Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity", *Springer-Verlag New York Inc.*, Environmental Management Vol. 30, pp. 492-507.

BWDB (2001) *Environmental and social management plan for Khulna-Jessore drainage rehabilitation project,* Bangladesh Water Development Board, Ministry of Water Resources, Government of Bangladesh.

BWDB (2005) *South west area integrated water resources management project,* Bangladesh Water Development Board, Ministry of Water Resources, Government of Bangladesh.

BWDB (2006) *Water Management Improvement Project (Revised),* Bangladesh Water Development Board, Ministry of Water Resources, Government of Bangladesh.

Catling, D., (1992) *Rice in Deep Water*, International Rice Research Institute, The Macmillan Press Ltd, p. 144.

Chowdhury, J. U., (2003) "Failure of flood control projects in wetland environment: Lesson for flood management", The Second Annual Paper Meet and International Conference on Civil Engineering, Dhaka, Bangladesh.

Chowdhury, J. U., (2009) "Sustainable Water Management: Need for Integrated Approach and Equity Considerations", Crossing Boundaries-Regional Capacity Building on IWRM and Gender & Water in South Asia: Training on Gender and Water, SaciWATERs/IWFM, BUET/BCAS, held during 11-13 July 2009 at IWFM, BUET, Dhaka, Bangladesh.

DAC (2002) *Glossary of Key Terms in Evaluation,* Development Assistance Committee.

Das, B., (1998) *Chingri Chas O Bebastapona (Shrimp culture and management),* Bangla Academy, Dhaka.

de Graaf, G., Born, B., Uddin, K. A. and Marttin, F., (2001) *Floods Fish & Fishermen. Eight years experience with floodplain fisheries, fish migration, fisheries modelling and* *fish biodiversity in the compartmentalization pilot project, Bangladesh*. The University Press Limited, Dhaka.

de Graaf, G., (2003a) "Dynamics of floodplain fisheries in Bangladesh, results of 8 years fisheries monitoring in the Compartmentalization Pilot Project." *Blackwell Publishing Ltd.*, Fisheries Management and Ecology, Vol-10, pp. 191-199.

de Graaf, G., (2003b) "The flood pulse and growth of floodplain fish in Bangladesh." *Blackwell Publishing Ltd.*, Fisheries Management and Ecology, Vol-10, pp. 241-247.

DFID (2004) *Management options and alternatives identified by FAP 17 project.* UK Department for International Development.

Dhondia, J. F. and Stelling, G. S., (2002) "Application of One Dimensional – Two Dimensional Integrated Hydraulic Model for Flood Simulation and Damage Assesment." *Delft Hydraulics,* Hydroinformatics, pp. 1-12.

DOF (1984) Fishery Resource Survey System (Gopalgonj District), Department of Fisheries, Bangladesh

DOF (2010) Fishery Resource Survey System (Gopalgonj District), Department of Fisheries, Bangladesh.

Edna, M. R, (2007) *Floodplain Inundation Simulation Using 2D Hydrodynamics Modelling Approach,* M.Sc. Thesis, International Institute for Geo-information Science and Earth Observation.

EGIS (1997) *Floodplain Fish Habitat.* Environment and GIS Support Project for Water Sector Planning, Bangladesh.

Ehrlich, P. R. and Ehrlich, A. H., (1991) *Healing the planet: Strategies for resolving the environmental crisis.* Reading, Mass.: Addison-Wesley Publishing Co.

Finlayson, C. M., Bailey, B. J. and Cowie. I. D., (1989) "Macrophyte Vegetation of the Magela Creek Floodplain, Alligator Rivers Region, Northern Territory." Supervising Scientist for the Alligator Rivers Region, Australian Government Publishing Service, Canberra.

GOB (2000) *Compartmentalization Pilot Project (FAP 20), Tangail.* Government of the People's Republic of Bangladesh, Ministry of Water Resources, Water Resources Planning Organization.

Grubaugh, J. W. and Anderson, R. V., (1988) "Spatial and temporal availability of floodplain habitat: Long-term changes at Pool 19, Mississippi River", American Midland Naturalist 119: 402–411.

Haile, A. T. and Rientjes, T. H. M., (2005) "Effects of lidar dem resolution in flood modelling: a model sentitivity study for the city of tegucigalpa, honduras", Workshop on Laser scanning, Enschede, The Netherlands.

Haque, A. K. M., Middendrop, H. A. and Hasan, M. R. (1996) "Status of small indigenous fish in the oxbow lakes of south-western Bangladesh."

Hassan, A., (2010) *A Decision Support Framework for Sustainable Land and Water Management in a Floodplain,* Ph.D. Thesis, Institute of Water and Flood Management, Bangladesh University of Engineering and Technology.

Hatipoğlu, M. A., Keskin, F. and Seyrek, K., (2007) "Floodplain delineation in mugla-dalaman plain using gis based river analysis system", State Hydraulics Works (DSI), Investigation and Planning Department Ankara, Turkey.

Hector, G., Priyanie, A. and Huber-Lee, A., (2005) "The Effects of Agricultural Irrigation on Wetland Ecosystems in Developing Countries," Discussion Paper on Comprehensive Assessment of Water Management in Agriculture, International Water Management Institute, Colombo, Sri Lanka.

IWM (2006) South West Regional Model, Institute of Water Modelling, Dhaka.

Junk, W. J., Bayley, P. B. and Sparks, R. E., (1989) "The Flood Pulse Concept in River-Floodplain Systems", In D. P. Dodge [ed.] , *International Large River Symposium,* Can. Spec. Publisher, Fish. Aquatic, Sci. 106, pp. 110-127.

Kiesel, J., Hering, D., Schmalz, B. and Fohrer, N., (2009) *A transdisciplinary approach for modeling macroinvertebrate habitats in lowland streams,* International Association of Hydrological Sciences, IAHS Publication 328.

Kingsford, R. T., (2000) “Review, Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia”, *Austral Ecology,* Vol. 25, pp. 109-127.

Lamberts, D., (2008) *Little impact, much damage: The consequences of Mekong River flow alterations for the Tonle Sap ecosystem,*–Modern Myths of the Mekong, Water and Development Publications, Helsinki University of Technology, Finland, pp. 3-18.

Lubchenco, J., Risser, P. G., A. C. Janetos, J. R. Gosz, B. D. Gold and Holland, M. M., (1993) “Priorities for an environmental science agenda for the Clinton-Gore Administration: Recommendations for transition planning.” Bulletin of the Ecological Society of America, Vol-74, pp. 4-8.

Mahfuzuddin, A., (1993) “Rights, Benefits and Social Justice: Keeping Common Property Freshwater Wetland Ecosystems of Bangladesh,” Fourth Common Property Conference, 16-19 June 1993, Manila, The Philippines, ICLARM Contribution No. 947, International Center for Living Aquatic Resources Management (ICLARM), Manila, The Philippines.

Middleton, B. A., (1999) “Succession and herbivory in monsoonal wetlands”, Wetlands Ecology and Management 6: 189–202.

Middleton, B. A., (2002) “The Flood Pulse Concept in Wetland Restoration, National Wetlands Research Center.”, USGS, Lfayette, Louisiana.

MoEF (1992) *National Environment Policy and Action Plan*, Ministry of Environment and Forests, Government of the People’s Republic of Bangladesh, Dhaka, Bangladesh.

MoWR (1999) *National Water Policy*, Ministry of Water Resources, Government of the People’s Republic of Bangladesh, Dhaka, Bangladesh.

MoWR (2010) *Annual Report 2008-09,* Ministry of Water Resources, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh.

MPO (1987) *Groundwater Resources of Bangladesh.* Technical Report No. 5. Master Plan Organization, Ministry of Water Resources, Government of Bangladesh. Harza Engineering USA in association with Sir MacDonald and Partners, UK, Met Consultant, USA and EPC Ltd, Dhaka.

Mustafa, M. G., (2009) *Changes of Aquatic Habitat and Fisheries Biodiversity at Two Small Scale Water Resources Projects in Narail*, M.Sc. Thesis, Institute of Water and Flood Management, Bangladesh University of Engineering and Technology.

Nazimuddin, M., (2005) *Changes of environmental Parameters due to Salinity Intrusion in the South East Region of Bangladesh*, M.Sc. Thesis, Institute of Water and Flood Management, Bangladesh University of Engineering and Technology.

Niering,W., (1994) "Wetland vegetation change: A dynamic process", Wetland Journal 6: 6–15.

Power, M. E., Sun, A., Parker, G., Dietrich, W. E. and Wotton, J. T., (1995) "Hydraulic food chain models: an approach to the study of food web dynamics in large rivers" *BioScience*, Vol. 45, pp. 159-167.

Rahman, M., Capristrano, D. A., Minkin, S. F. and Halder, S. (1999) Experience of community managed wetland habitat restoration. In: *Sustainable Fisheries Management in Bangladesh*, Middledorp, H. A. J., Thompson, P. M. and Pomeroy, R. S., (eds.) ICLARM Conf. Proc. 58, pp 111-21.

Ratner, B.D., Ha, D.T., Kosal, M., Nissapa, A. and Chanphengxay, S., (2004) Undervalued and Overlooked: Sustaining Rural Livelihoods Through Better Governance of Wetlands. *World Fish Center Studies and Reviews* No. 28. Available from: http://www.worldfishcenter.org.

Reid, M. A. and Brooks, J. J., (2000) "Detecting Effects of Environmental Water Allocations in Wetlands of The Murry-Darling Basin, Australia", *John Wiley & Sons Ltd.*, Regulated Rivers: Research & Management, Vol. 16, pp. 479-496.

Richardson, C. J., (1994) "Ecological functions and human values in wetlands: A framework for assessing forestry impacts", Wetlands 14:1-9.

Shannon, C.E. and Wiener, W., (1949) "The Mathematical Theory of Communication" Urbana University of Illinois Press, Chicago, USA, p. 117.

Simpson, E.H., (1949). Measurement of diversity. *Nature,* London, pp. 163, 688.

Sparks, R. E., Bayley, P. B., Kohler, S. L. and Osborne, L. L., (1990) "Disturbance and recovery of large floodplain rivers", Environmental Management 14: 699–709.

SRDI (2008) Soil and Land Resources Information System, Soil Resource Development Institute, Ministry of Agriculture, Government of Bangladesh

Talukder, B., Nobukazu, N. and Rashid, M.S., (2009) "State and Management of Wetlands in Bangladesh", Springer Japan, Vol. 5(1), pp. 1860-1871.

Tsai, C. and Ali, M. Y., (1997) *Open-water Fisheries of Bangladesh.* University Press Ltd., Bangladesh.

USACE (2009) *River Analysis System HEC-RAS*, Hydrologic Engineering Center, Hydraulic Reference Manual version 4.0.

USAID (2005) *Municipal development fund report.* United States Agency for International Development.

USEPA (1989) *The Ecology of Stream and Riverine Habitats of the Great Basin Region.* US Environmental Protection Agency, US Department of Interior, US Fish and Wildlife Service. Biological report 85 (7.24), pp-6.

van der Valk, A. G., (1981) "Succession in wetlands: A Gleasonian approach", Ecology 62: 688–696.

Vannote, R. L., Minshall, G. M., Cummins, K. W., Sedel, J. R. and Cushing, C. E., (1980) “The river continuum concept”, Can. J. Fish. Aquat. Dci. Vol. 37, pp. 130-137.

Walker, A. J., Dowling, T. and Veitch S., (2006) “An assessment of catchment condition in Australia”, *ELSEVIER Science Ltd.*, Ecological Indicators, Vol. 6, pp. 205-214.

Ward, J. V. (1998) “Riverine landscapes: biodiversity patterns, disturbance regimes and aquatic conservation”, Biol. Conservation. Vol. 83, pp. 267-278.

WARPO (1993) *Southwestern Regional Project,* Flood Action Plan 4, Main Vol., Water Resources Planning Organization, Ministry of Water Resources, Bangladesh.

WARPO (1995a) *Fisheries Studies and Pilot Project.* Bangladesh Flood Action Plan (FAP17), Final Report, Main Vol., Water Resources Planning Organization, Ministry of Water Resources, Bangladesh.

WARPO (2001) *National Water Management Plan Development Strategy,* Water Resources Planning Organization, Ministry of Water Resources, Bangladesh.

WFC (2006) *The world fish newsletter.* The World Fish Center.

WFC (2007) *The world fish newsletter.* The World Fish Center.

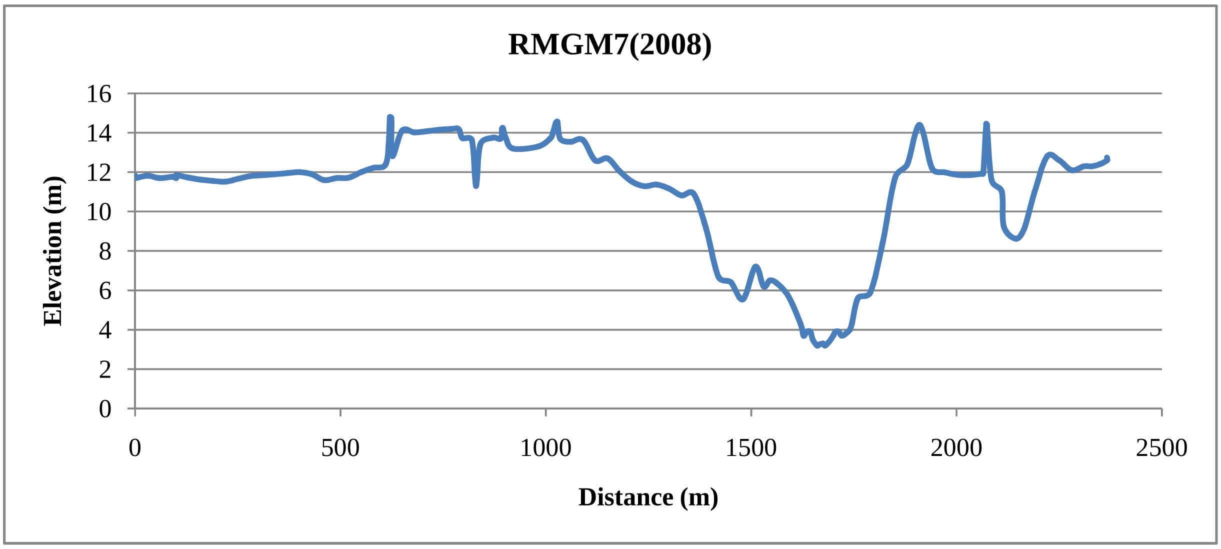
WL | Delft Hydraulics (2010) *SOBEK River/Estuary User Manual,* SOBEK Help Desk, version 2.12.002.

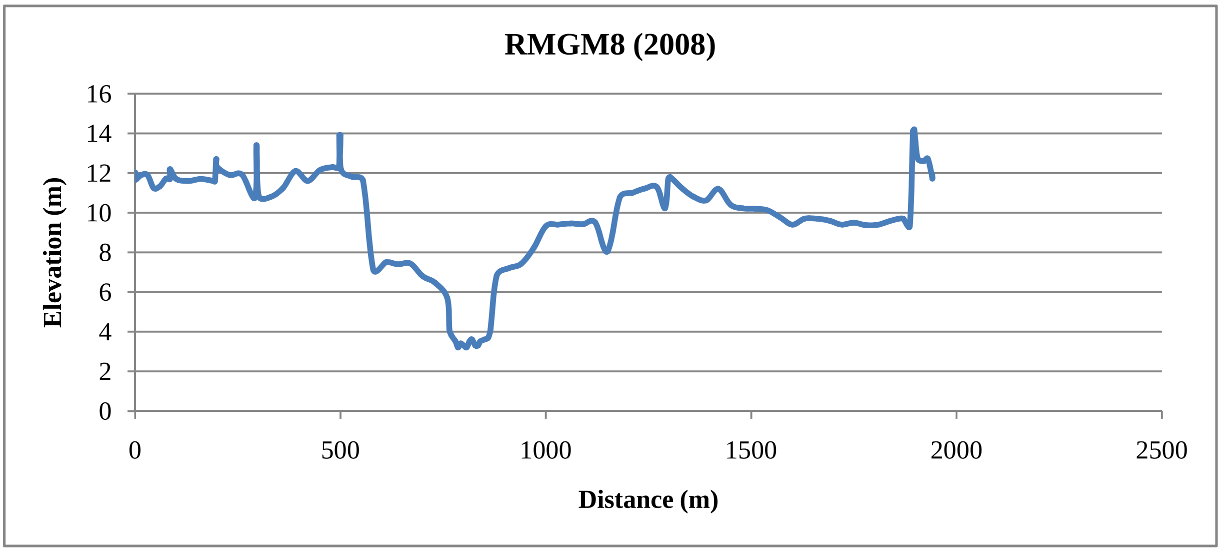
Zalewski, M., (2006) “Flood pulses and river ecosystem robustness”, *IAHS Publications,* 305, pp. 143-154.

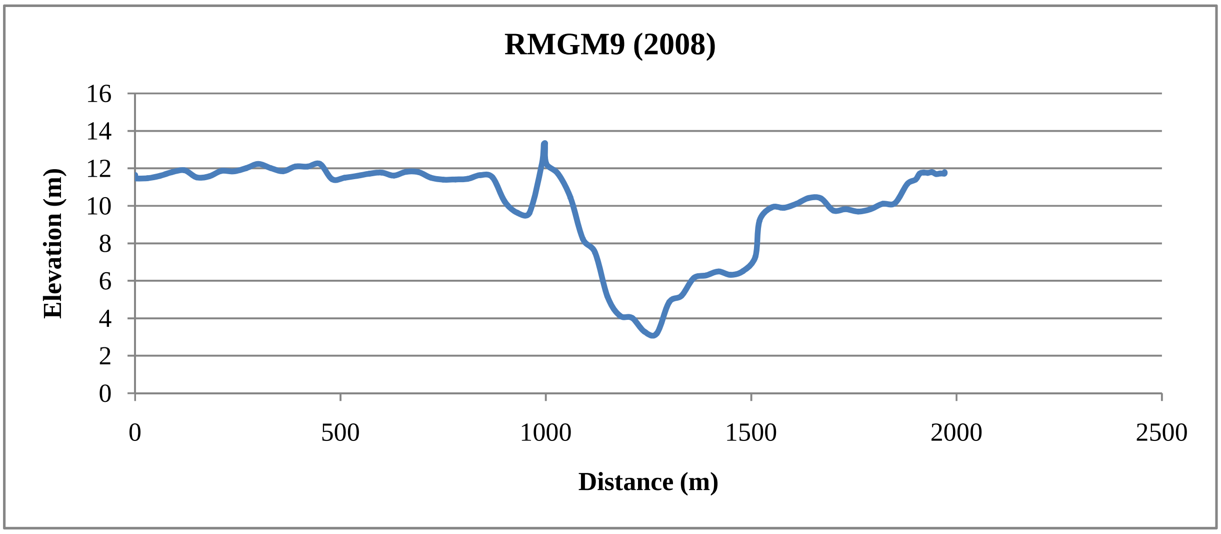
Appendix A

Hydrological Data

Cross sections



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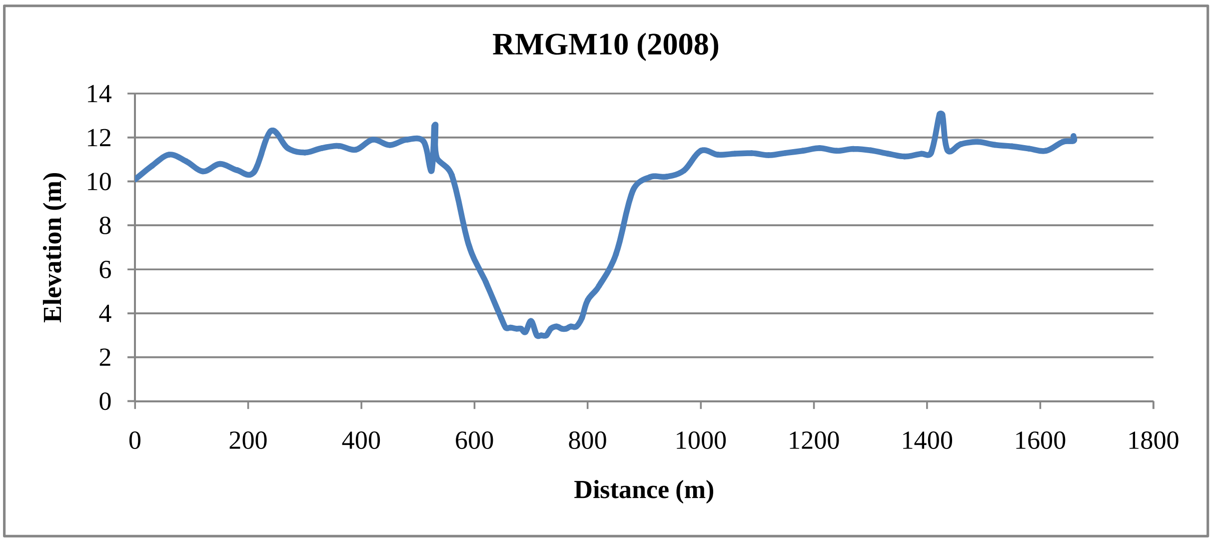
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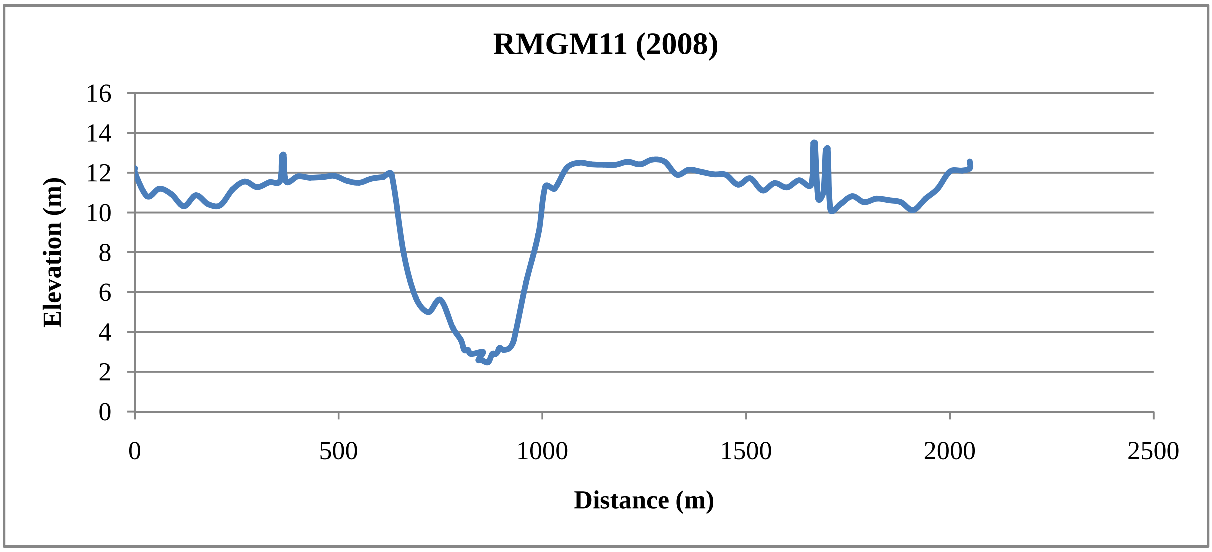
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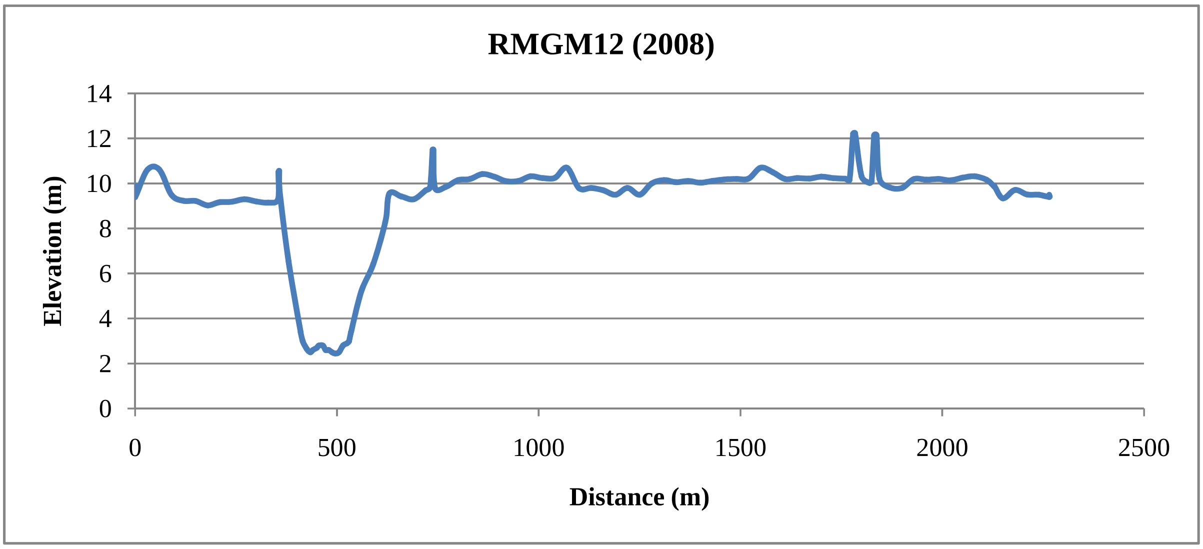
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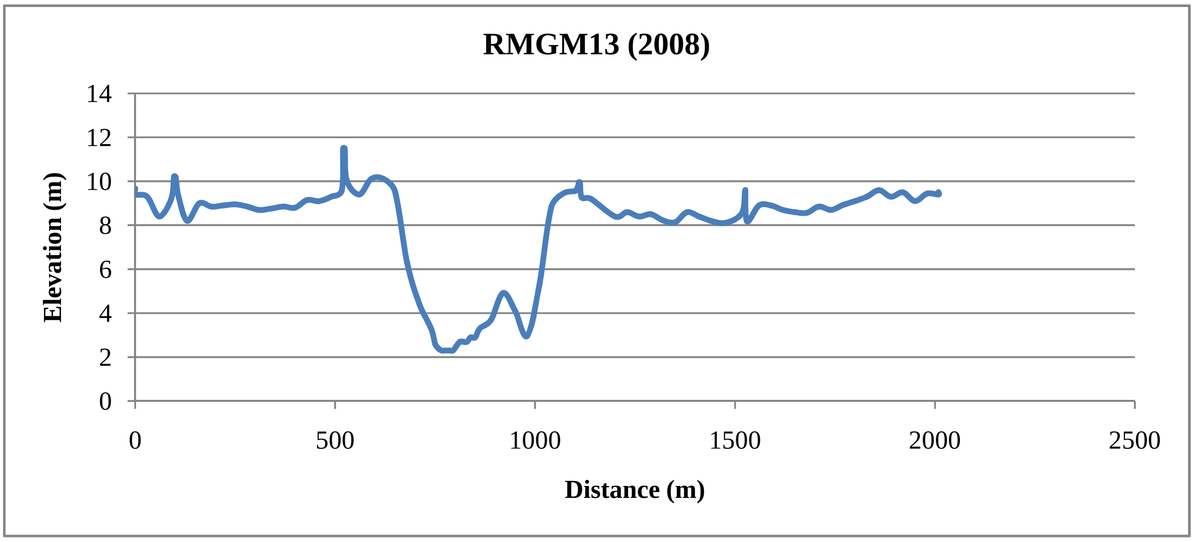
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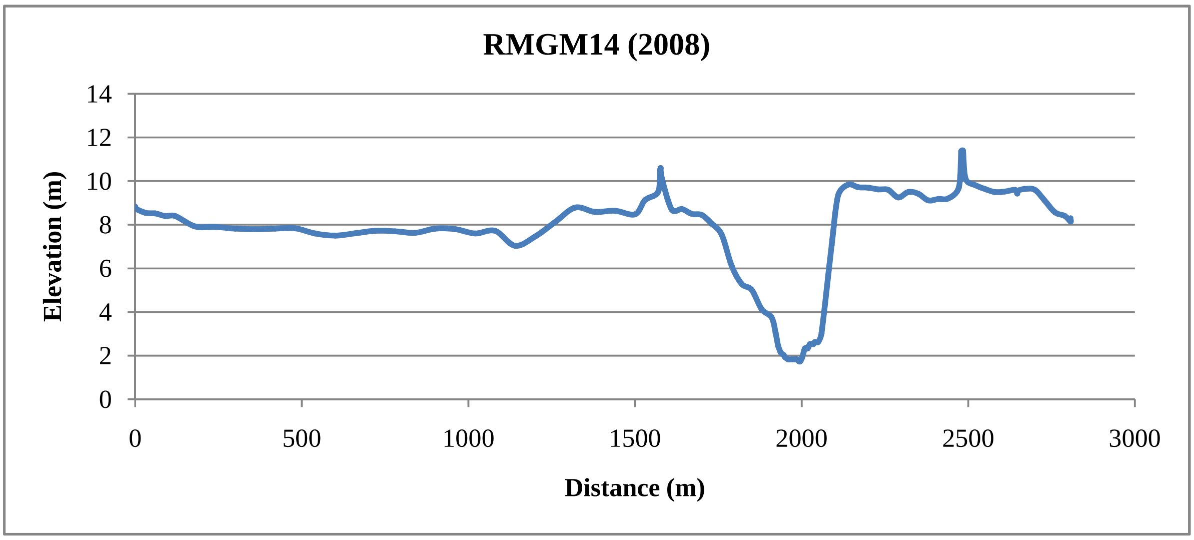
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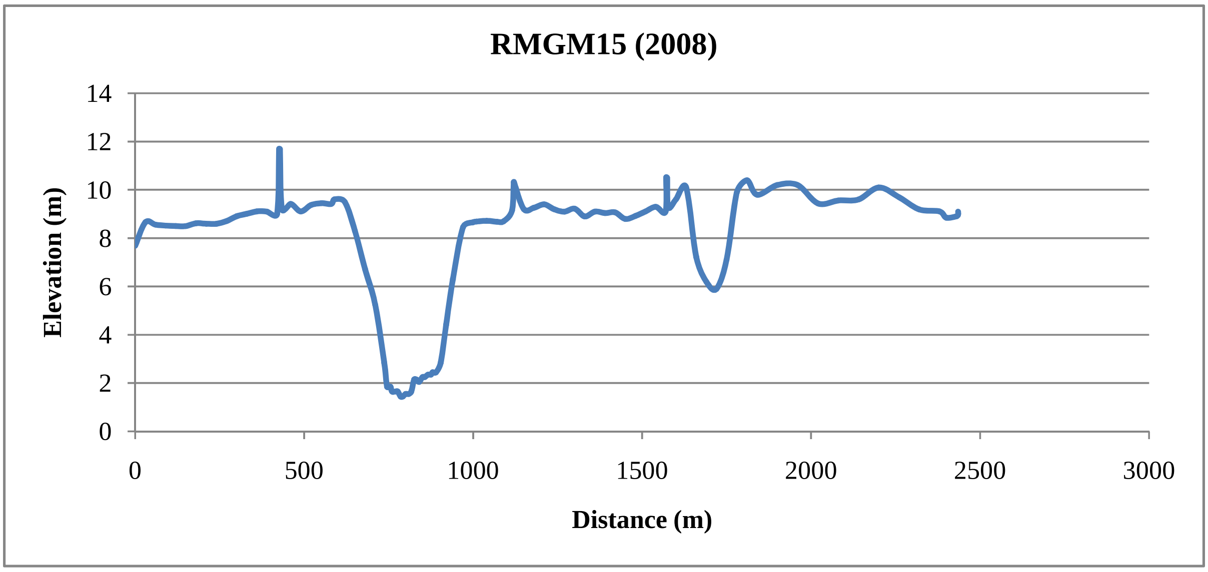
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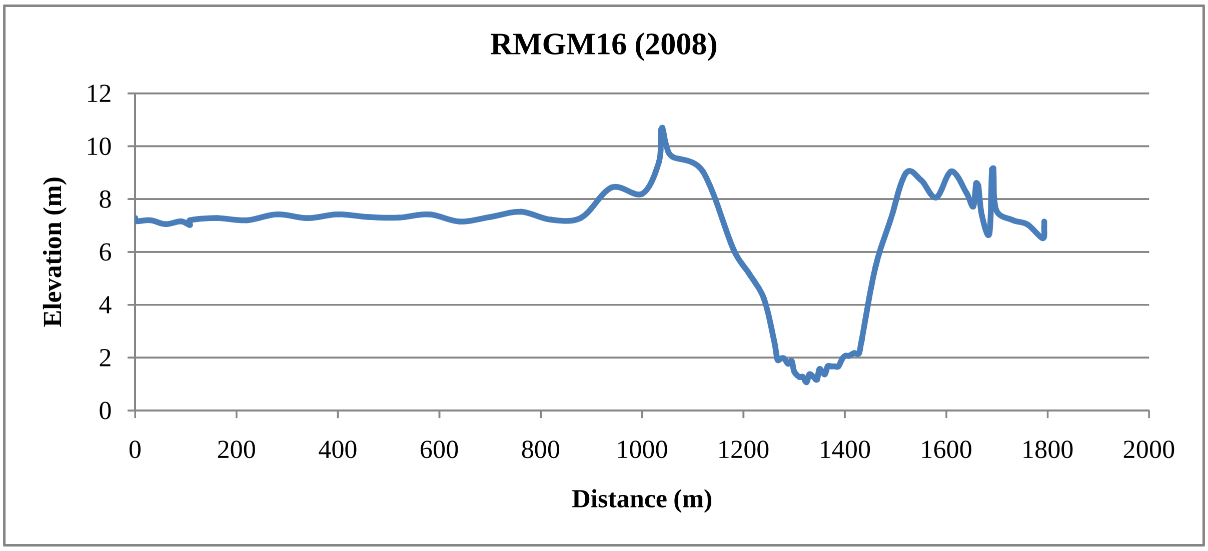
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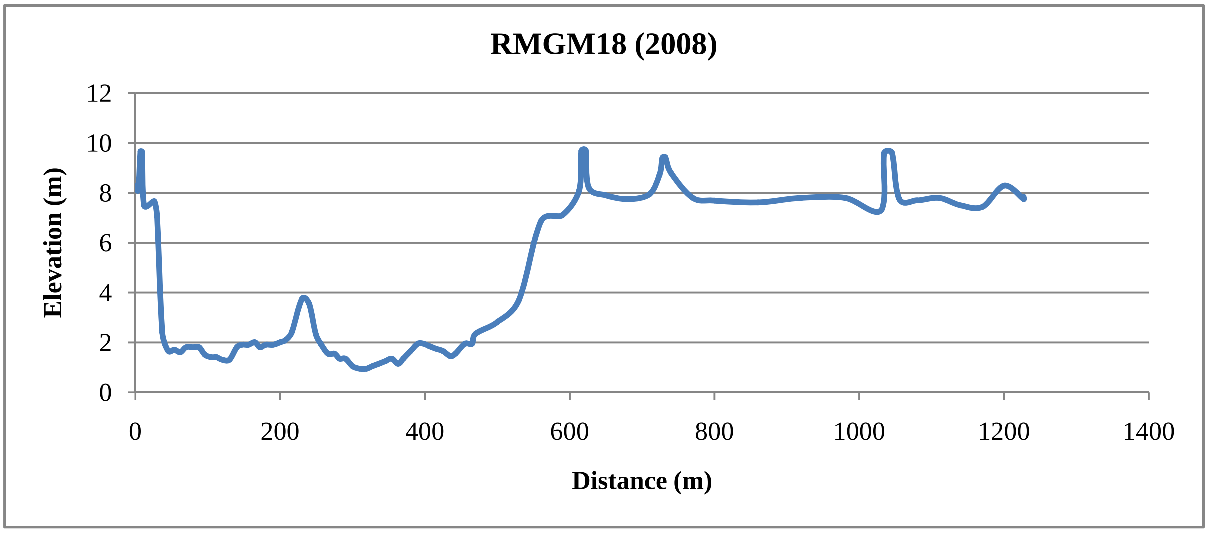

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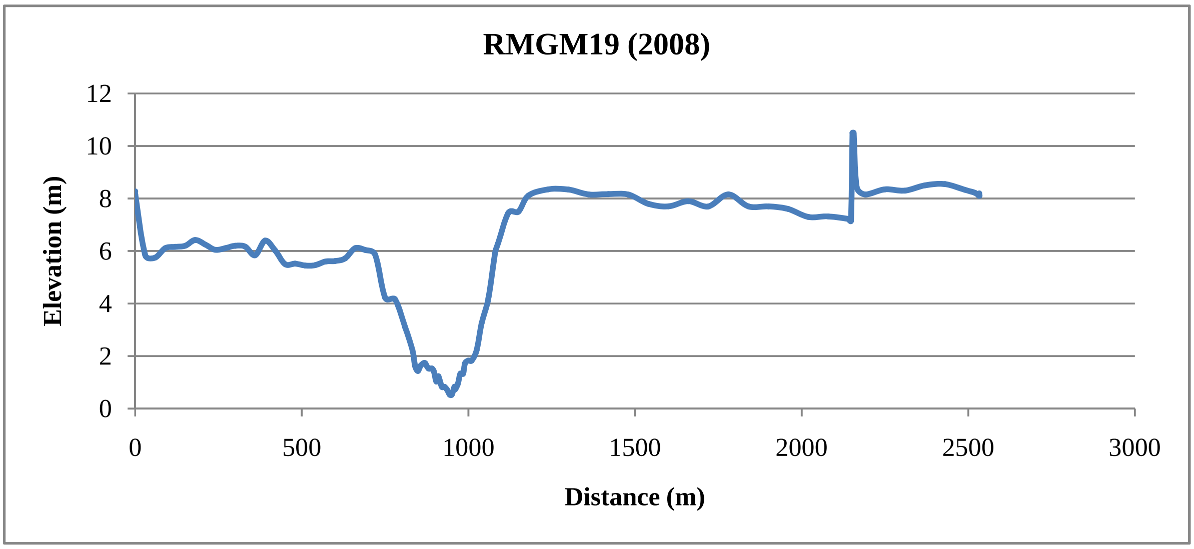

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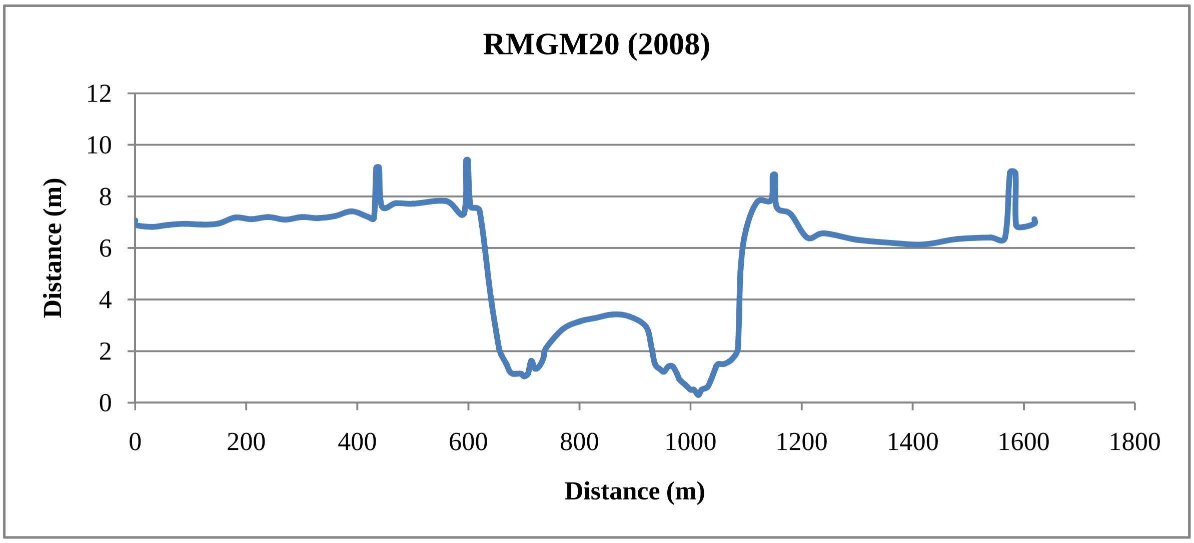
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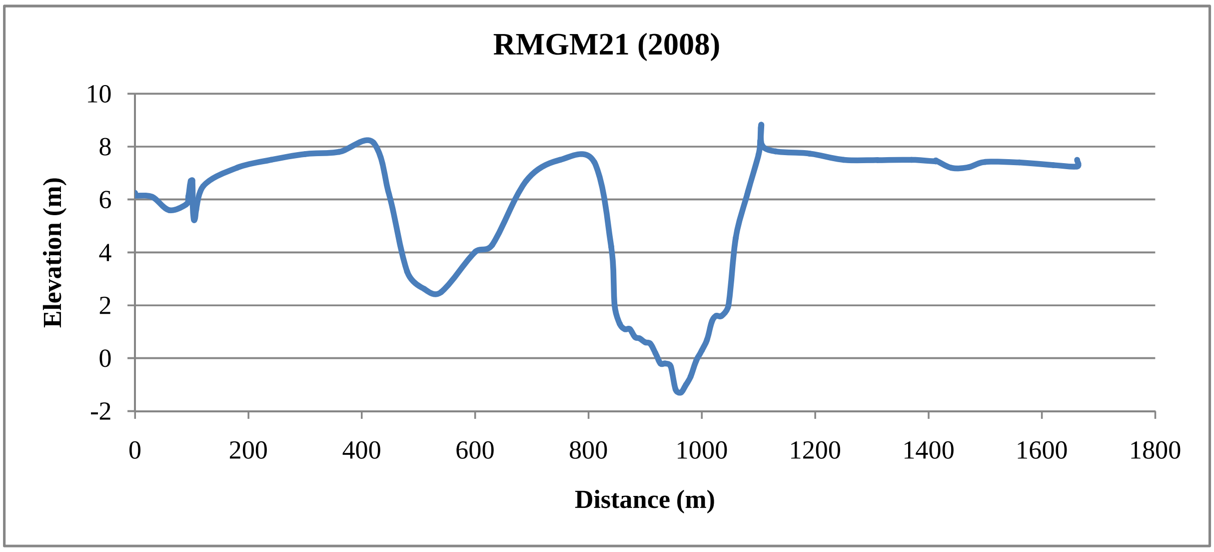
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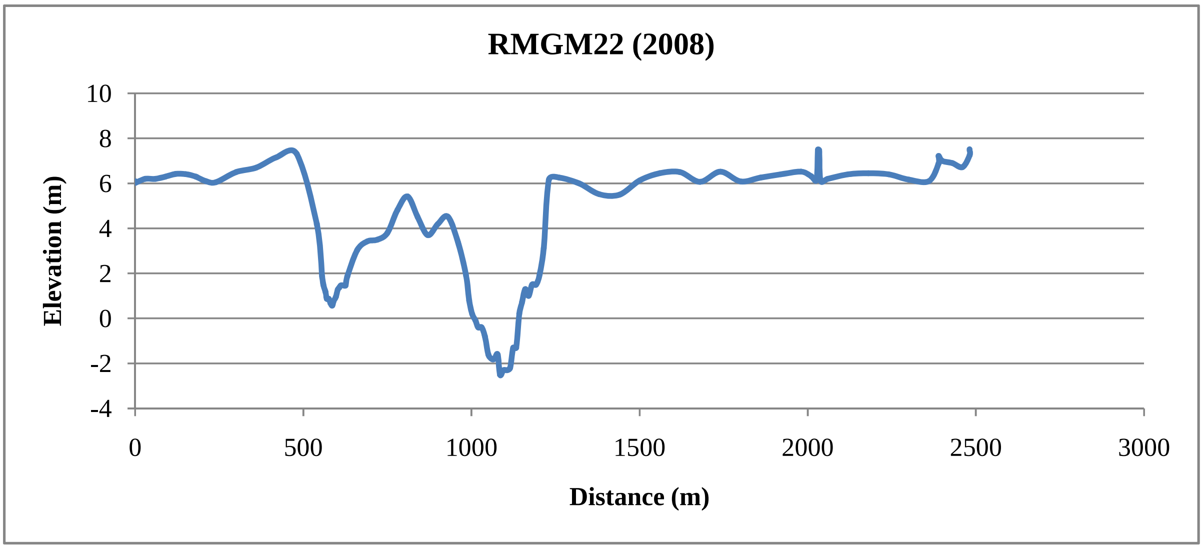
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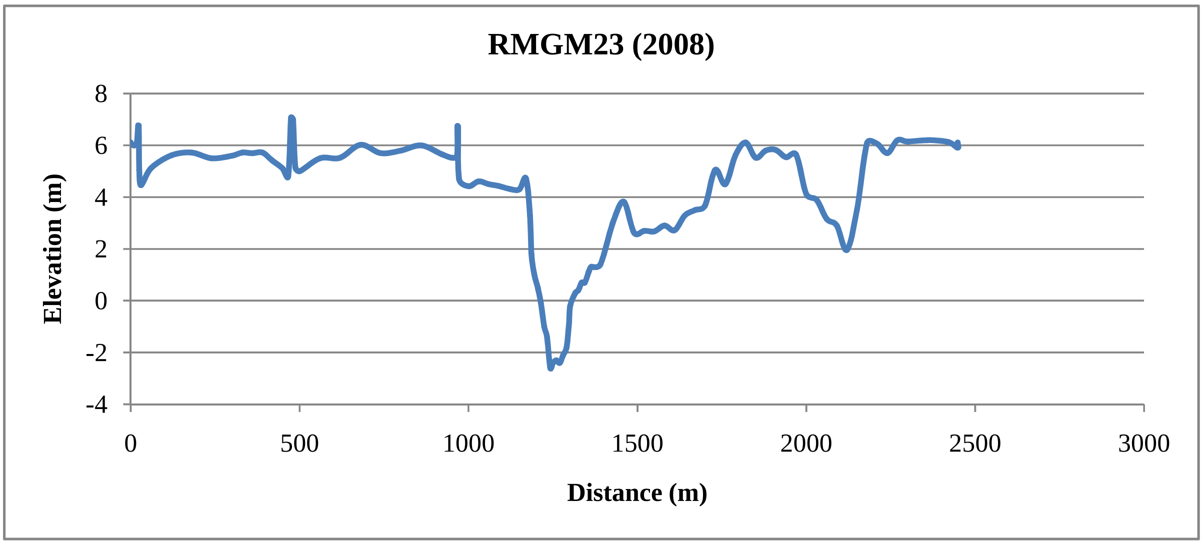
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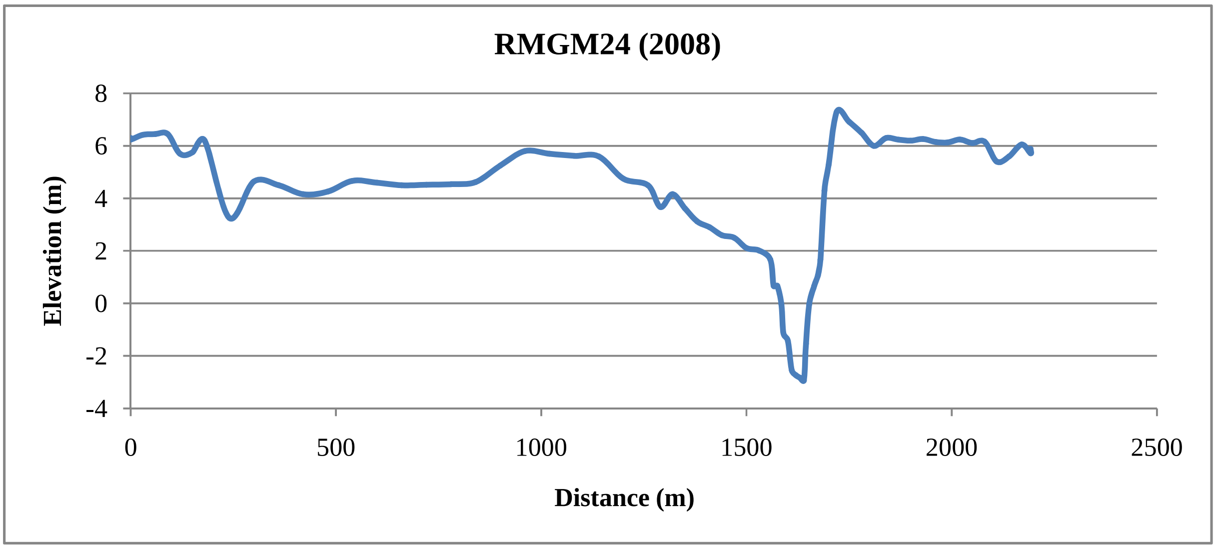
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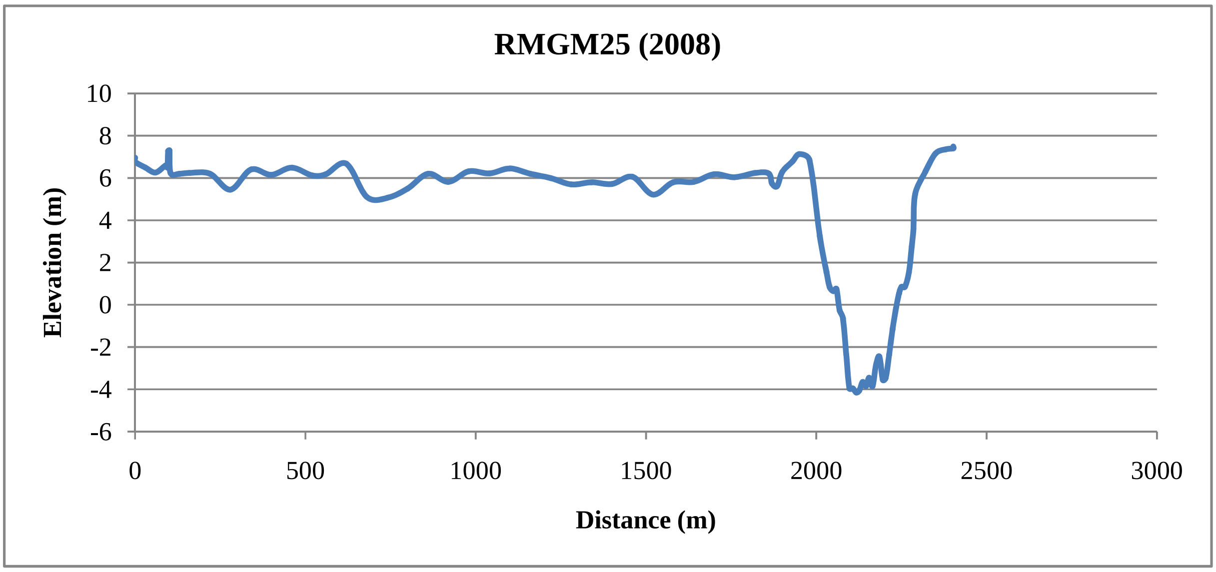
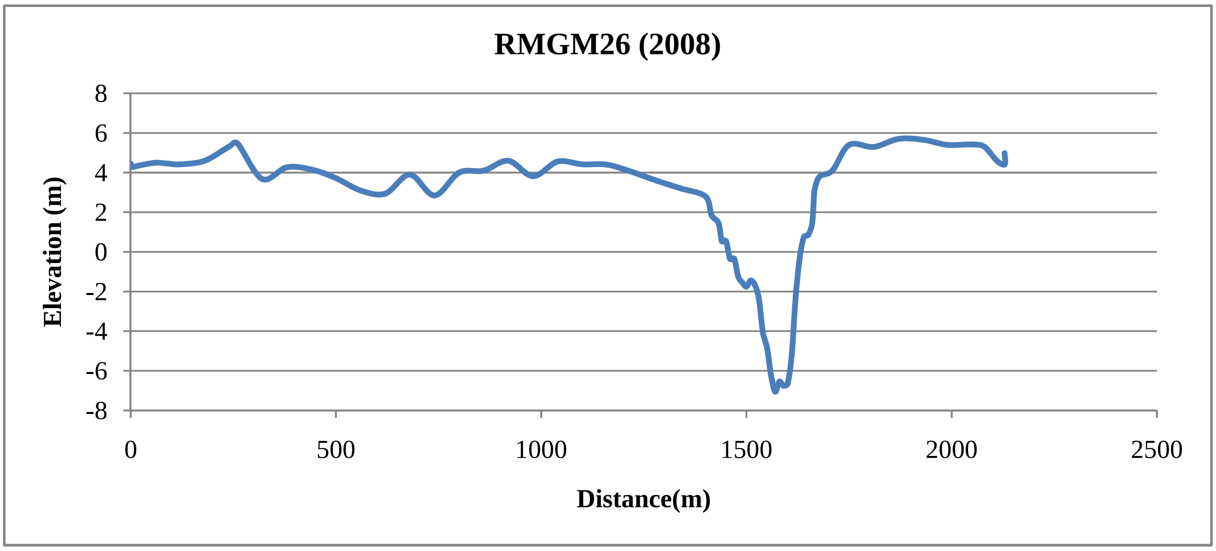
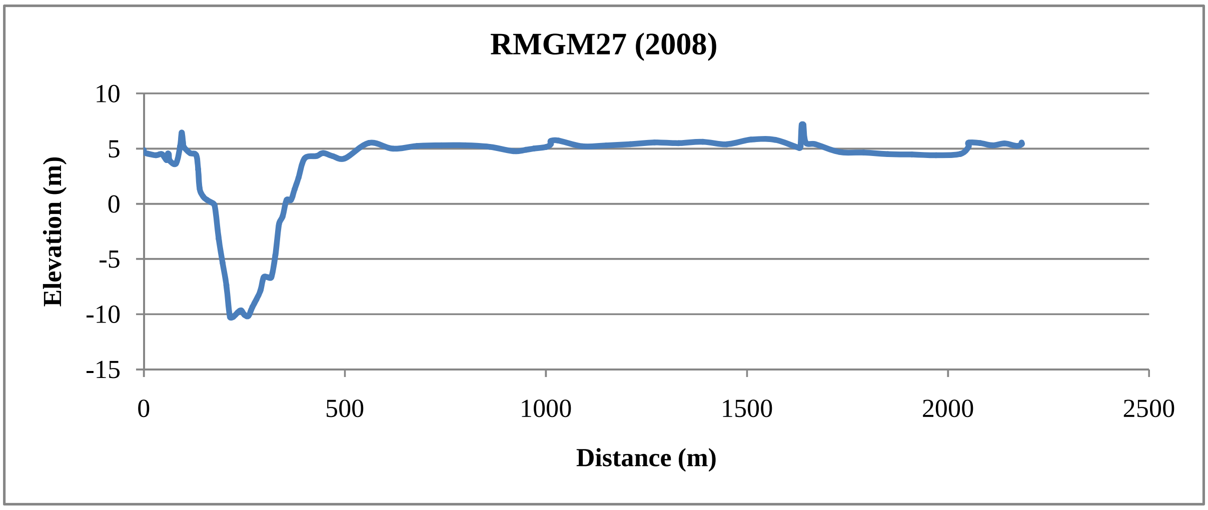
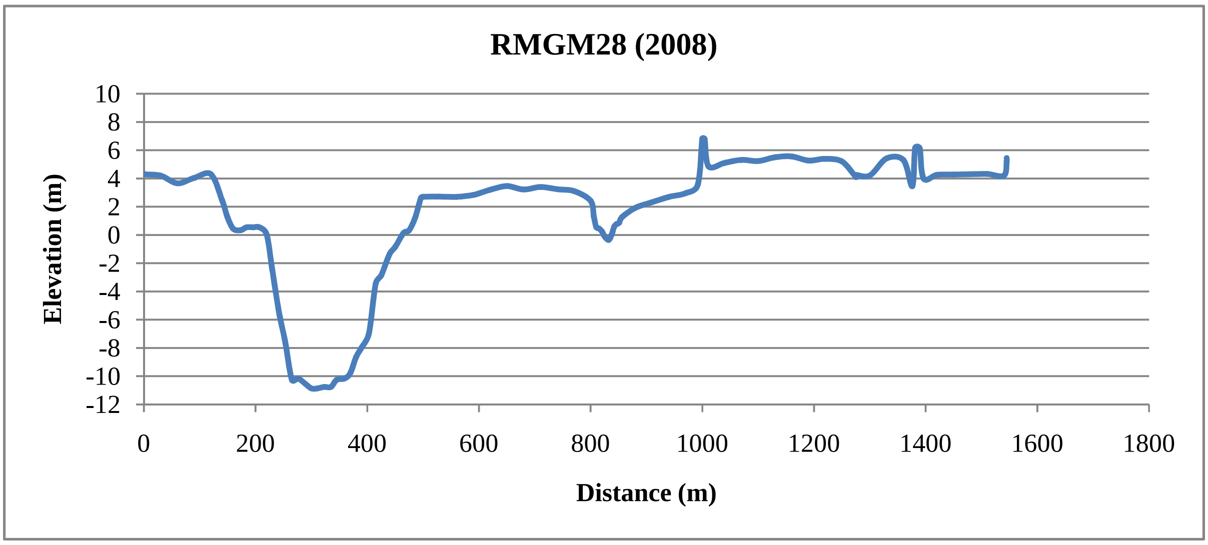
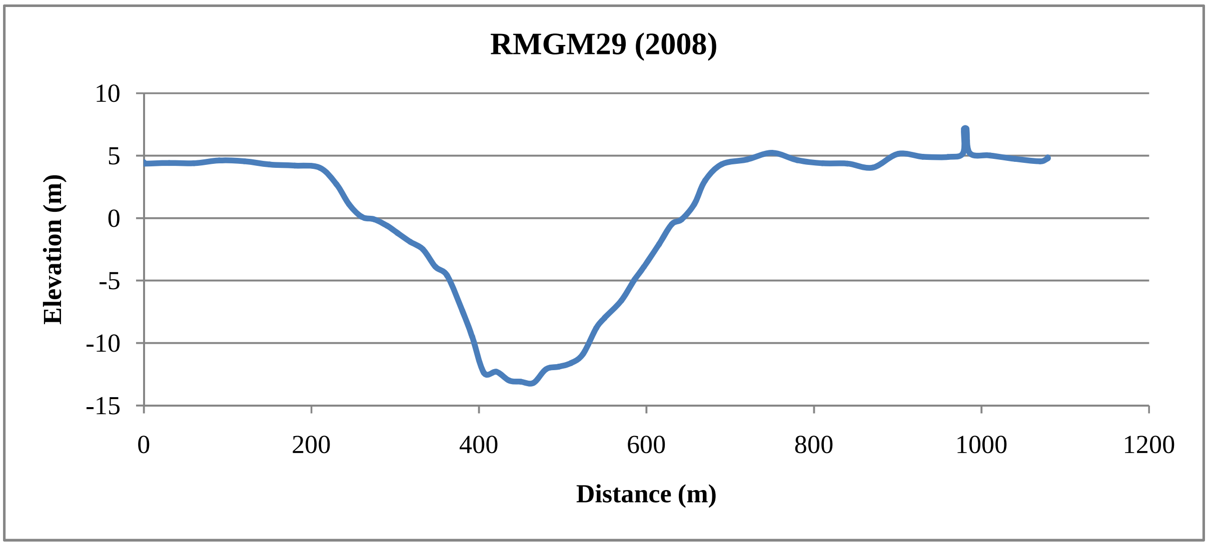
Elevation (m)
8
6
4
2
0
-2
-4
0
500
1000
1500
2000
2500
Distance (m)

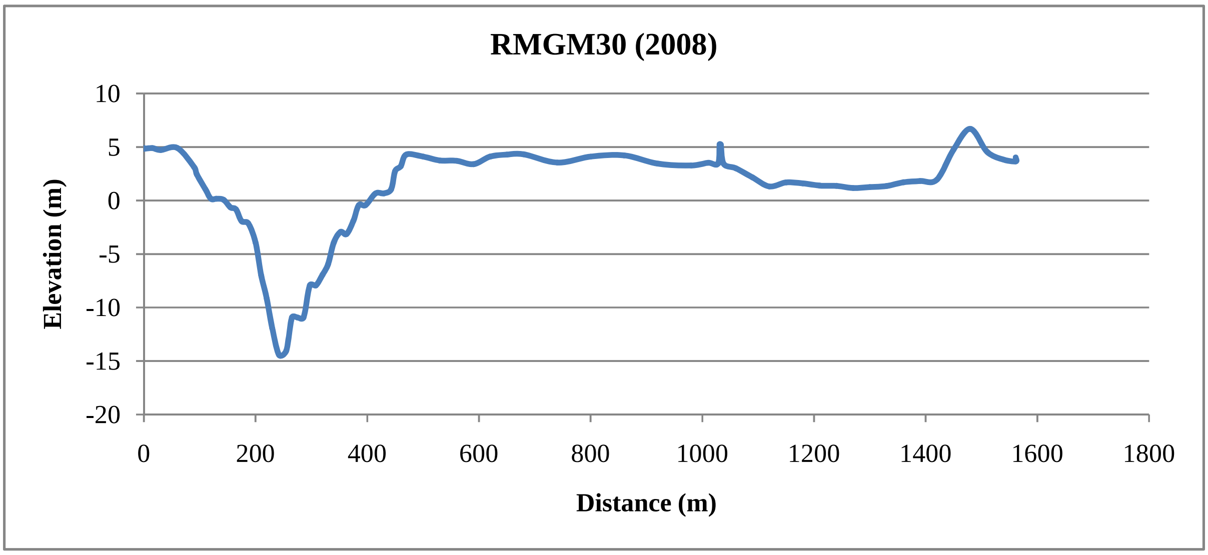

RMGM25 (2008)
Elevation (m)
10
8
6
4
2
0
-2
-4
-6
0
500
1000
1500
2000
2500
3000
Distance (m)

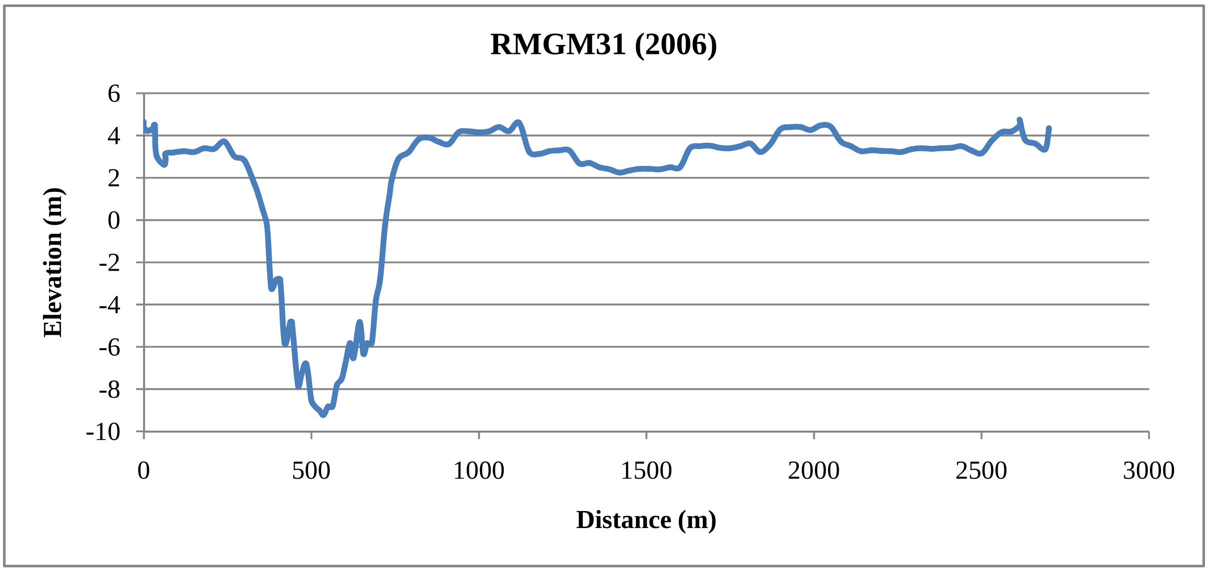

RMGM26 (2008)
Elevation (m)
8
6
4
2
0
-2
-4
-6
-8
0
500
1000
1500
2000
2500
Distance(m)

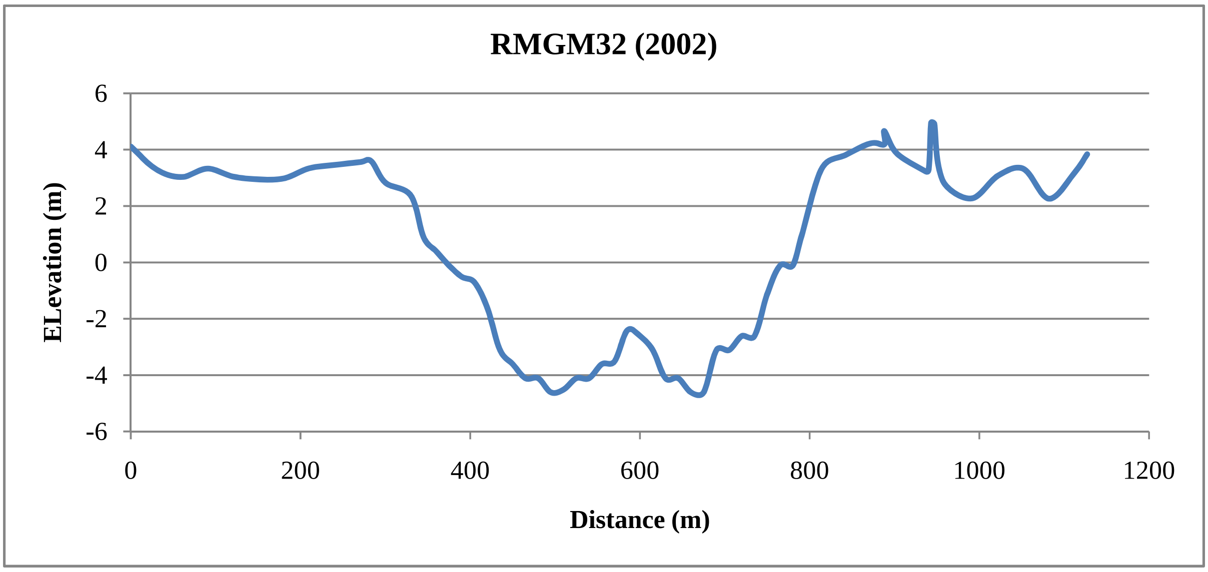

RMGM27 (2008)
Elevation (m)
10
5
0
-5
-10
-15
0
500
1000
1500
2000
2500
Distance (m)


RMGM28 (2008)
Elevation (m)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0
200
400
600
800
1000
1200
1400
1600
1800
Distance (m)

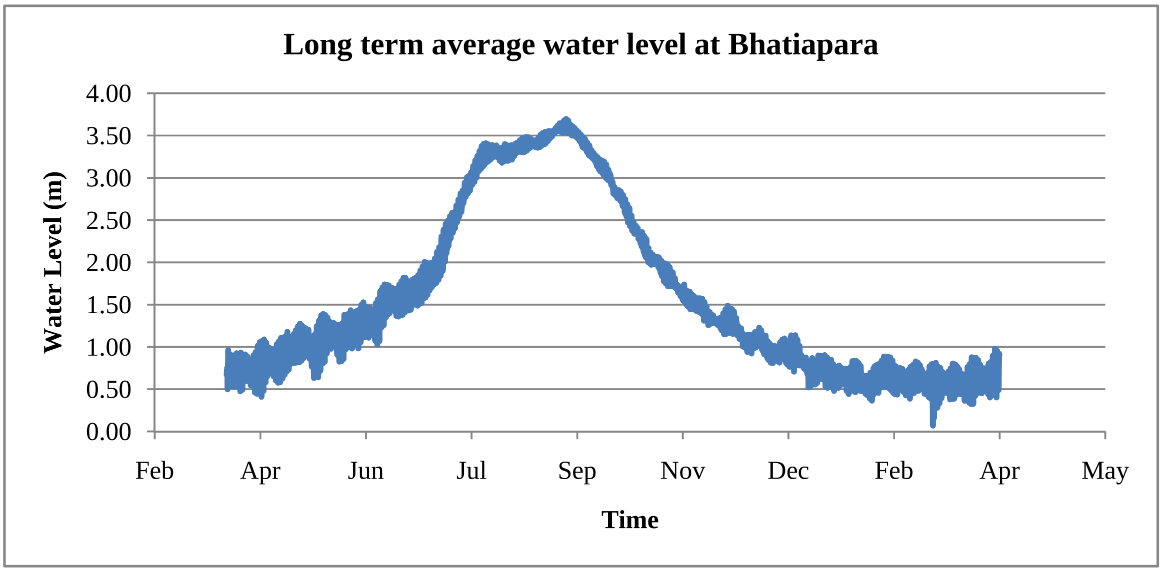

RMGM29 (2008)
Elevation (m)
10
5
0
-5
-10
-15
0
200
400
600
800
1000
1200
Distance (m)


RMGM30 (2008)
Elevation (m)
10
5
0
-5
-10
-15
-20
0
200
400
600
800
1000
1200
1400
1600
1800
Distance (m)

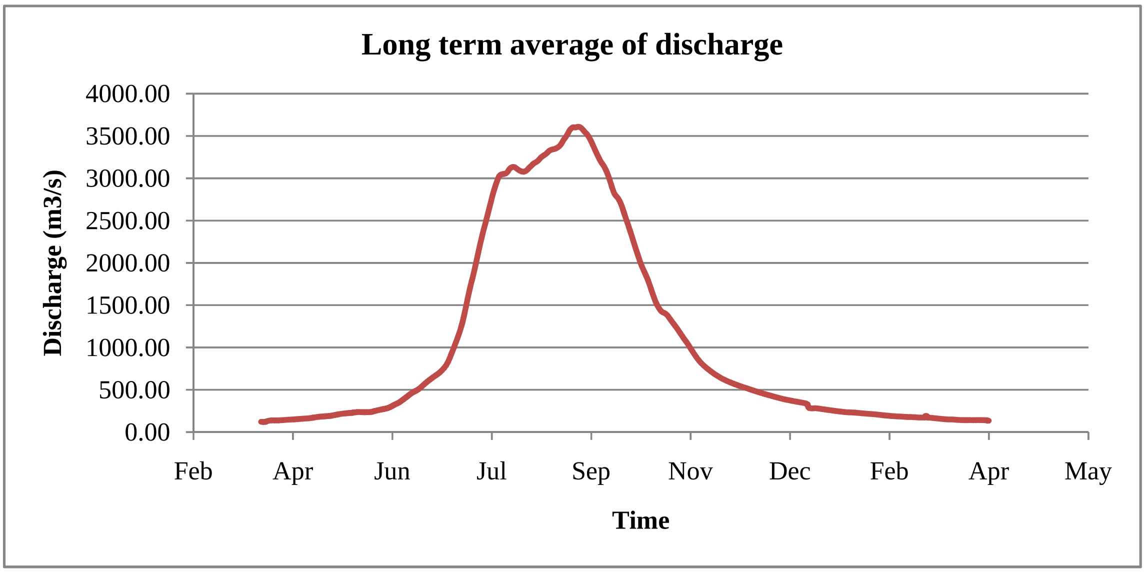

RMGM31 (2006)
Elevation (m)
6
4
2
0
-2
-4
-6
-8
-10
0
500
1000
1500
2000
2500
3000
Distance (m)


RMGM32 (2002)
ELevation (m)
6
4
2
0
-2
-4
-6
0
200
400
600
800
1000
1200
Distance (m)

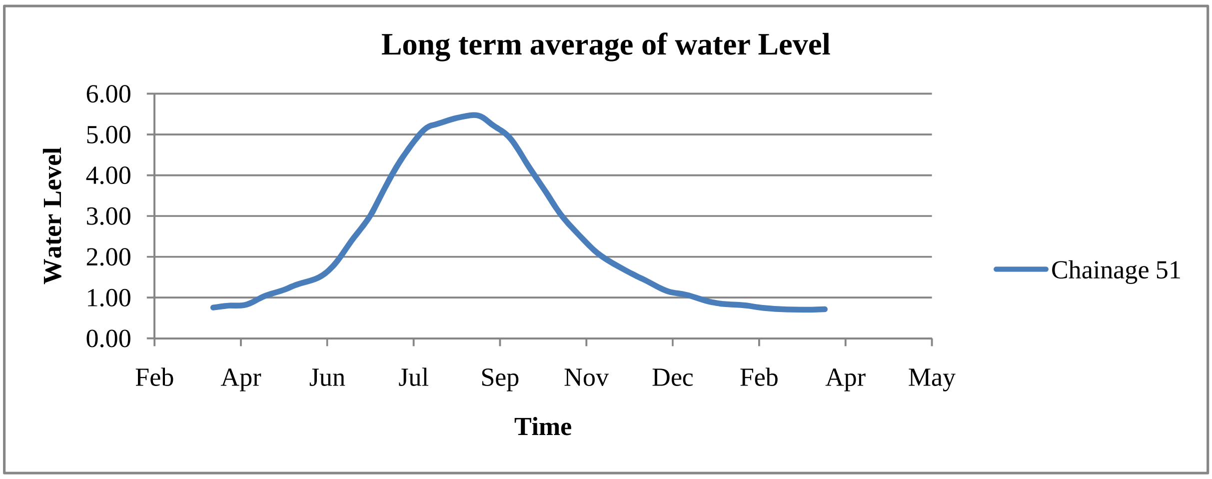
Downstream boundary condition

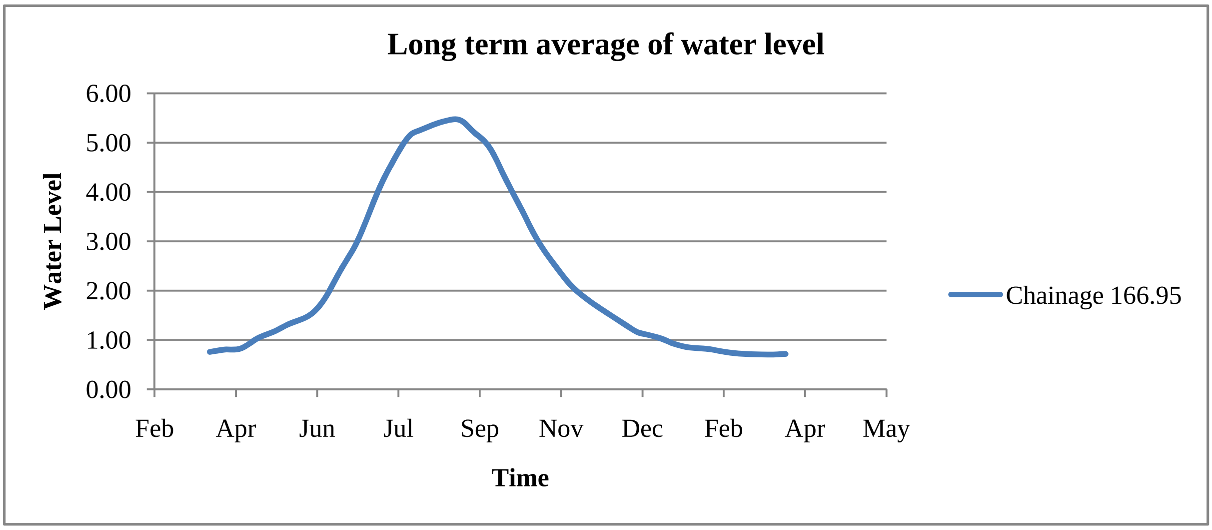


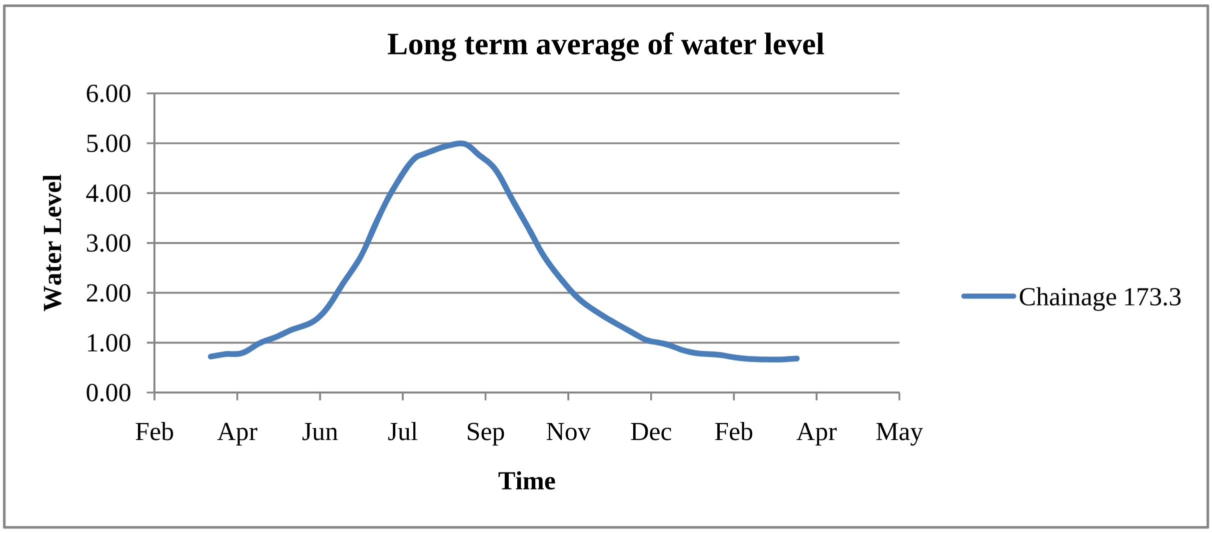
Upstream boundary condition

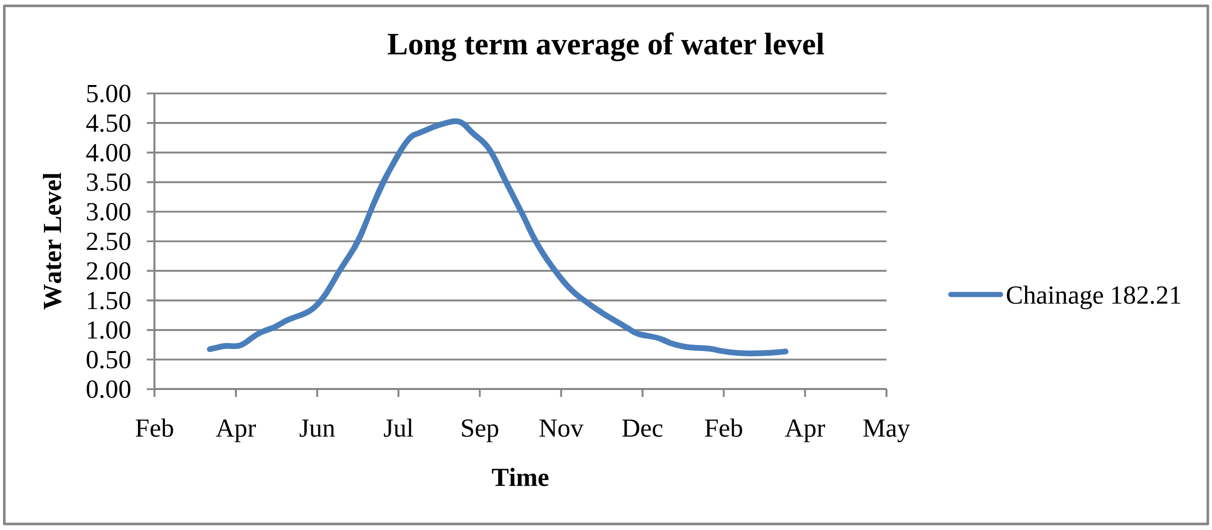


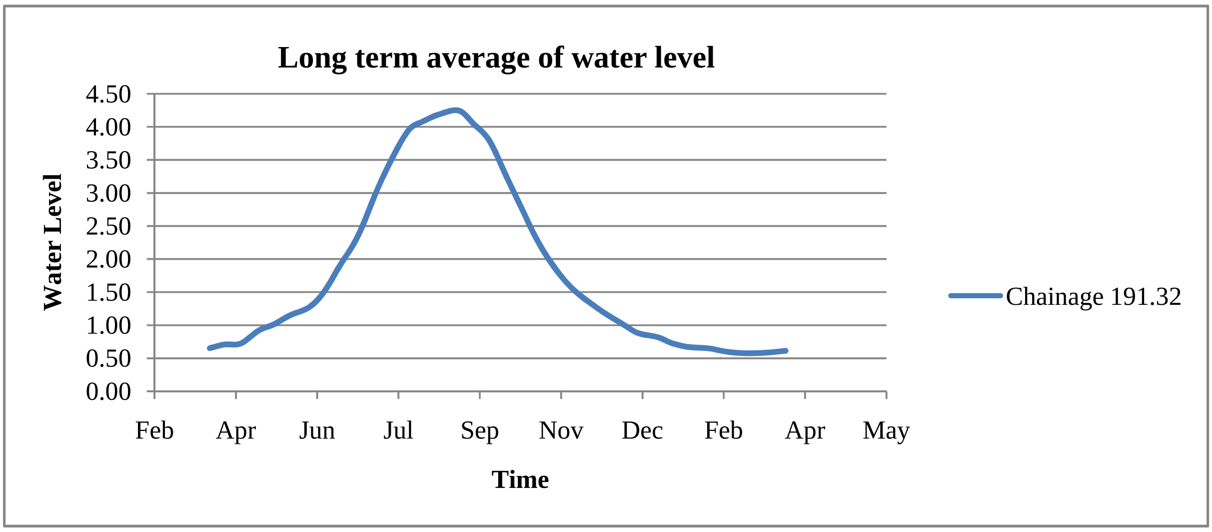
Long term average of water level at different chainage






Long term average of water level
Water Level
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Feb
Apr
Jun
Jul
Sep
Nov
Dec
Feb
Apr
May
Time
Chainage 173.3

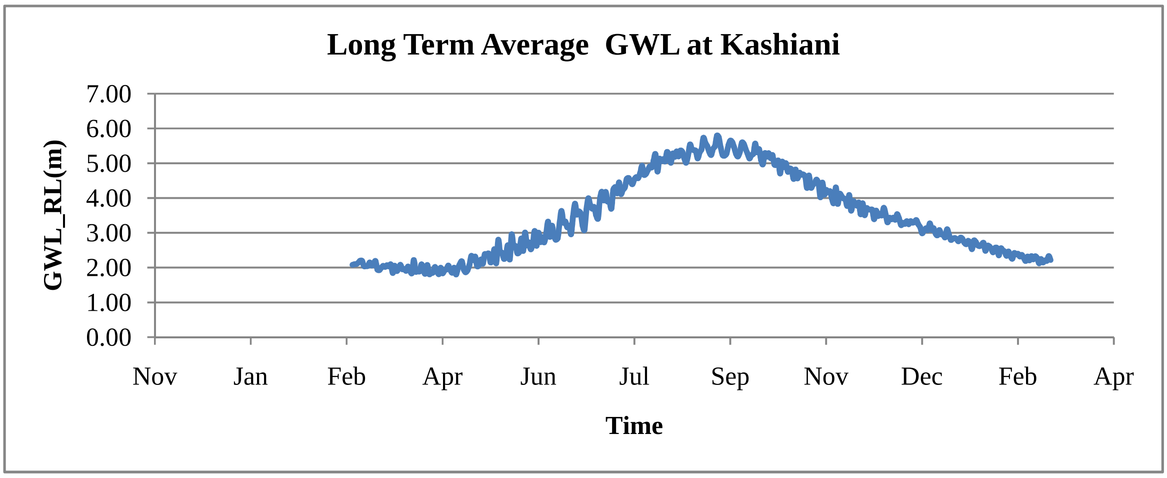

Long term average of water level
Water Level
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Feb
Apr
Jun
Jul
Sep
Nov
Dec
Feb
Apr
May
Time
Chainage 182.21

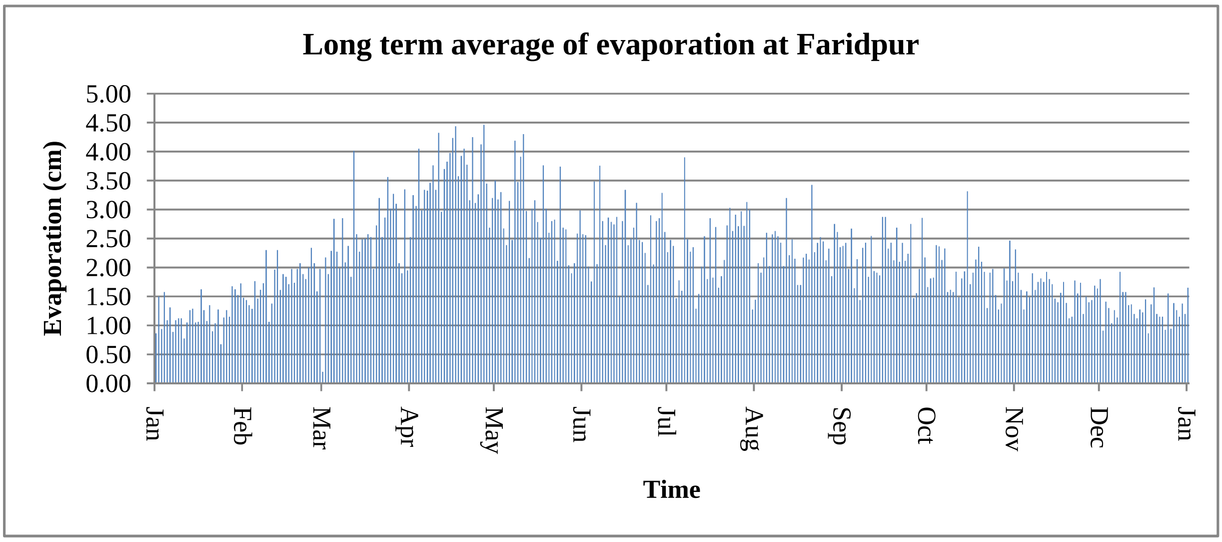

Long term average of water level
Water Level
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Feb
Apr
Jun
Jul
Sep
Nov
Dec
Feb
Apr
May
Time
Chainage 191.32

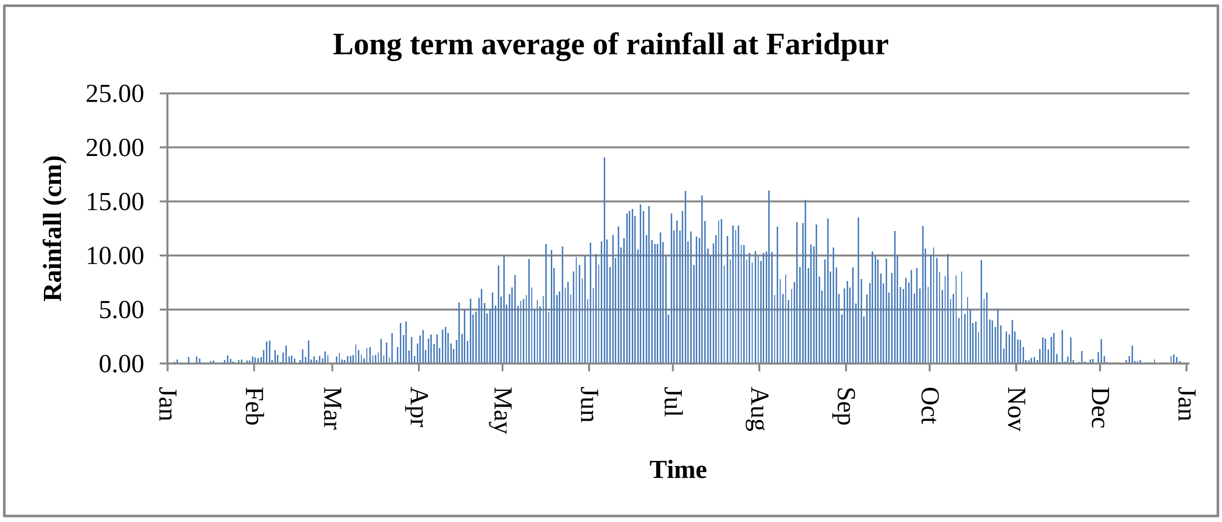
NAM parameters for internal catchments

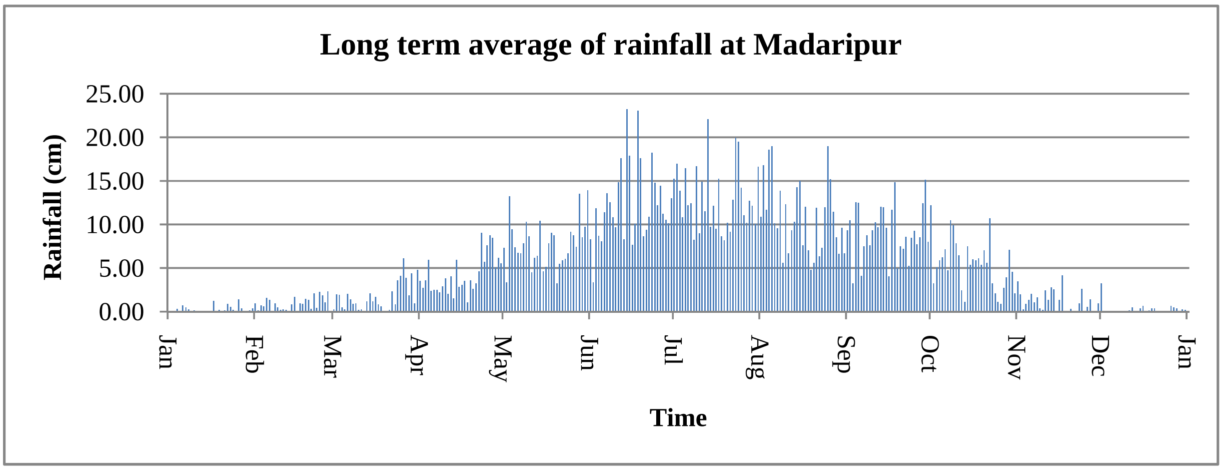
Catchments	Area	Sy	KO-inf	TG	GWLBF0	GWLBF1	CKIF	CKBF	CK1	CK2
SW-12	1142	0.05	0.08333	0	3.2	1.65	1000	500	24	24

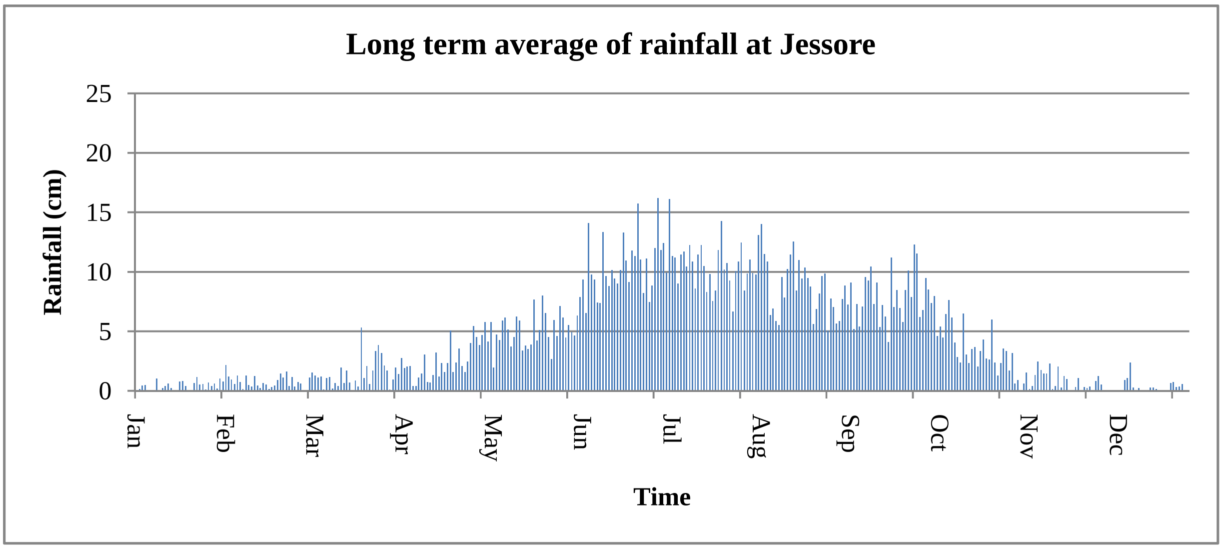
Meteorological Data



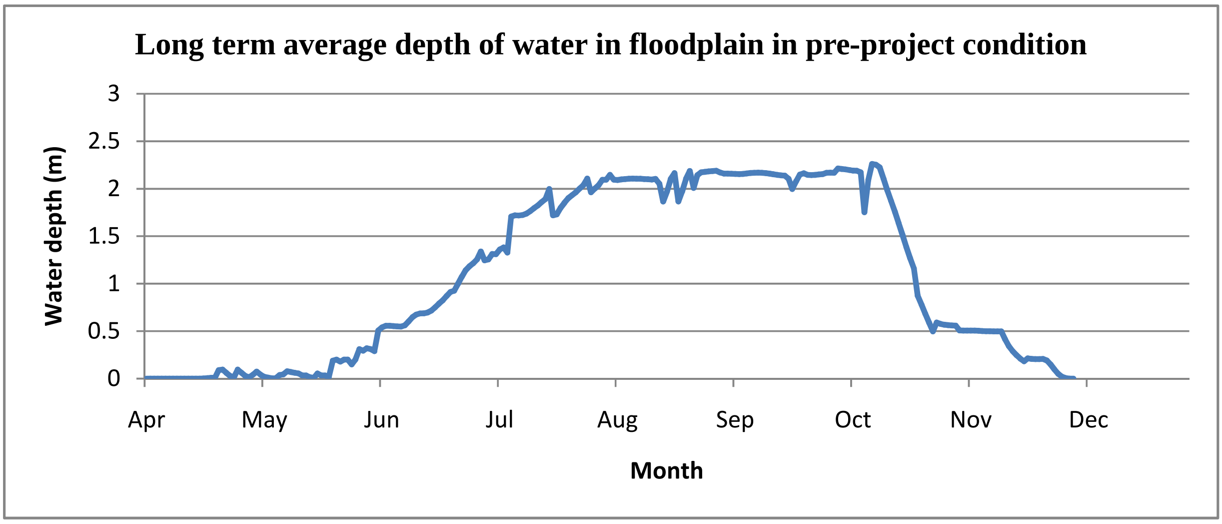


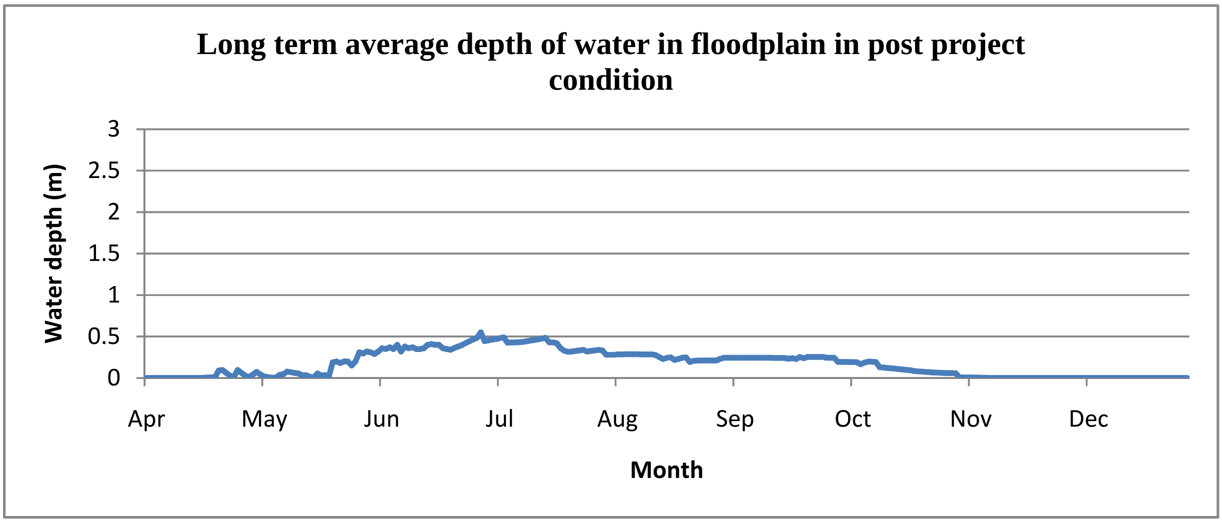

Long term average of rainfall at Faridpur
Rainfall (cm)
25.00
20.00
15.00
10.00
5.00
0.00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Time

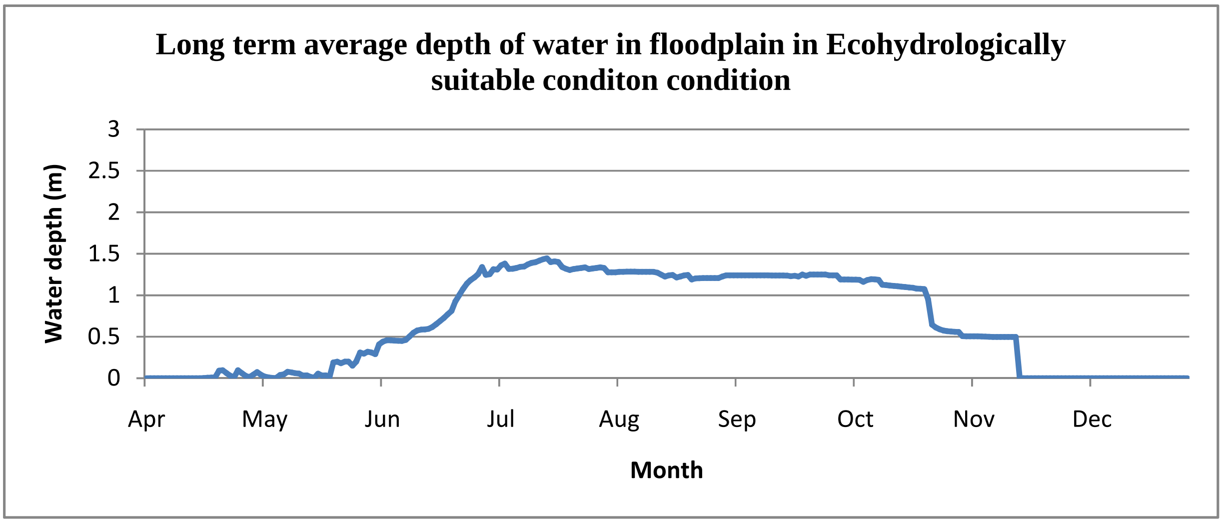

Long term average of rainfall at Madaripur
Rainfall (cm)
25.00
20.00
15.00
10.00
5.00
0.00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Time


Long term average of rainfall at Jessore
Rainfall (cm)
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Time

Generated hydrograph






Long term average depth of water in floodplain in Ecohydrologically suitable conditon condition
Water depth (m)
3
2.5
2
1.5
1
0.5
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

Appendix B

Ecological Data

Indicative fish species diversity of different fish habitats in and around the study area

Scientific Name	Local Name	Habitat Type				
		River	Khal	Beel	Floodplain	Culture pond
Labio rohita	Rui	P	A	P	P	P
Catla catla	Catla	P	A	P	P	P
Hilsha ilisha	Ilish	P	A	A	A	A
Rita rita	Rita	P	A	A	A	A
Rasbora rasbora	Darkina	P	P	P	P	A
Mystus aor	Aor	P	A	P	P	A
Botia dario	Rani	P	A	A	A	A
Godusia chapra	Chapila	P	A	A	P	A
Nandus nandus	Vada	P	A	P	A	A
Ciprinus carpio	Carpu	P	A	P	P	P
Labio calbasu	Calbaus	P	A	P	A	P
Wallagu attu	Boal	P	A	P	P	A
Channa panchtatus	Taki	P	P	P	P	A
Mystus vitatus	Tangra	P	P	P	P	A
Puntius ticto	Puti	P	P	P	P	A
Lepidosephalus guntia	Gutum	P	P	P	P	A
Heteropneutes fossilis	Shing	P	A	P	P	A
Clarias batrachus	Magur	P	A	P	A	A
Macrognathus aculatus	Baim	P	A	P	P	A
Amblypharingodon mola	Mola	P	P	P	P	A

Scientific Name	Local Name	Habitat Type				
		River	Khal	Beel	Floodplain	Culture pond
Anabas testudineus	Koi	A	A	P	P	A
Pinius reba	Icha	P	P	P	P	A
Macrobrachium sp	Golda	A	A	A	A	P
Chanda sp	Chanda	P	P	P	P	A
Colisa fasciata	Kolisa	A	A	P	P	A
Channa striatus	Shole	A	A	P	P	A
Channa marulia	Goger	P	A	A	A	A
Aila coila	kajoli	P	A	A	A	A
Chela cachius	Chala	P	P	P	P	A
Davario devario	Patasi	P	A	A	A	A
Gudusia chapra	Chaplla	P	A	A	A	A
Mastacembalus armatus	Guchi	P	P	P	P	A
Corica soborna	Kaski	P	A	P	A	A
Chitala chitala	Chitol	P	A	A	A	A
Barbonymus gonionotus	Sorputi	P	A	A	A	P
Ompok pabda	Pabda	P	A	A	A	A
Xenentodon cancila	Kakila	P	A	P	P	A
Tenopharingodon idela	Grss crap	A	A	A	A	P
Aristicthyes nobilis	Bighead crap	A	A	A	A	P

Here, A=Absent and P=Present

Appendix C

Field Survey

Baseline data

Cropping pattern by land type

Land Type	Kharif-I (March-June)	Kharif-II (July-October)	Rabi (Nov-February)	% of area
HH	B. Aman	T. Aman (HYV)	Wheat	15
MH	Jute	T. Aman (HYV)	Boro (HYV)	25
ML	Fallow	T. Aman (Local)	Khesari, Boro (HYV)	15
LL	Fallow	Fallow	Boro (HYV)	45

Crop calendar

Crop name	Seedling		Transplanting/Sowing		Harvesting	
	Start	End	Start	End	Start	End
B. Aus (local)			End Apr	Mid May	Mid Aug	End Aug
T. Aman (HYV)	Early June	End June	End July	End Aug	Early Nov	End Nov
T. Aman (Local)	Early June	End June	End July	End Aug	Early Nov	End Nov
Boro (HYV)	End Oct	Mid Nov	Mid Dec	Mid Feb	Mid Apr	Mid May
Wheat			End Oct	Mid Nov	End Feb	Mid Mar
Khesari			Mid Oct	Mid Nov	Mid Mar	End Mar
Jute			End Mar	Mid Apr	Early Aug	Early Sep

Some spot heights inside the study area taken during topographic survey

X_COOR	Y_COOR	RL
565070.521	470903.819	3.667
565070.521	470903.819	3.667
565083.014	470891.350	3.913
565079.279	470904.575	3.926
565076.012	470924.287	3.582
565116.926	470919.916	3.907
565169.147	470895.382	3.433
565124.666	470891.178	3.405
565222.810	470882.076	3.272
565161.423	470892.965	3.302
565225.728	470904.510	3.513
565204.466	470869.465	3.262
565267.995	470912.849	3.573
565218.575	470852.366	3.247
565286.848	470906.789	3.483
565248.542	470868.858	3.119
565235.045	470844.934	3.086
565300.629	470916.767	3.602
565251.876	470847.644	3.173
565324.189	470921.317	3.718
565284.523	470868.356	3.105
565280.315	470843.561	3.069
565353.803	470927.944	3.719
565299.520	470841.303	3.204
565324.630	470869.374	3.114
565376.473	470929.673	3.707
565329.345	470839.826	3.206
565409.541	470936.908	3.736
565365.151	470873.920	3.240
565353.800	470835.672	3.390
565436.982	470943.074	3.959
565400.366	470873.308	3.291
565380.016	470818.161	3.718
565468.396	470945.984	4.003
565409.780	470831.991	3.619
565446.552	470878.612	3.509
565505.214	470944.480	4.177
565439.901	470842.513	3.591
565542.257	470950.323	4.210

X_COOR	Y_COOR	RL
565503.740	470887.850	3.675
565478.395	470851.796	3.656
565496.201	470861.634	3.766
565541.227	470892.884	3.792
565569.814	470957.809	6.293
565594.871	470930.492	6.268
565504.760	470846.600	3.785
565582.432	470920.620	3.953
565554.064	470841.834	4.066
565483.976	470832.806	3.792
565567.970	470821.211	4.090
565587.175	470807.403	4.131
565447.127	470788.032	3.877
565539.658	470712.304	3.976
565531.987	470742.390	3.963
565423.834	470811.943	3.792
565505.577	470725.184	3.868
565560.620	470676.897	3.918
565415.906	470798.600	3.802
565534.224	470653.985	4.049
565477.448	470735.828	3.832
565401.222	470786.421	3.826
565502.305	470660.243	3.890
565411.260	470754.123	3.909
565446.706	470747.905	3.789
565466.386	470677.577	3.856
565446.650	470747.805	3.795
565385.554	470806.678	3.849
565438.333	470689.941	3.792
565409.612	470759.160	3.845
565354.977	470805.684	3.707
565404.145	470711.417	3.736
565378.823	470767.280	3.725
565329.149	470792.590	3.687
565337.596	470767.399	3.603
565370.284	470727.341	3.915
565317.392	470810.073	3.436
565302.914	470773.303	3.526
565345.574	470723.091	3.732

X_COOR	Y_COOR	RL
565298.233	470810.860	3.446
565264.009	470789.931	3.260
565302.944	470735.125	3.603
565277.879	470812.622	3.124
565245.960	470795.843	3.189
565269.299	470815.794	3.018
565254.042	470751.238	3.692
565263.471	470729.452	3.648
565261.022	470784.986	3.467
565232.609	470749.089	3.435
565277.037	470702.246	3.772
565254.673	470751.854	3.617
565285.696	470687.787	4.013
565207.763	470727.116	3.407
565231.433	470738.235	3.637
565284.861	470687.205	4.040
565284.886	470687.181	4.042
565237.356	470719.465	3.765
565314.578	470676.824	3.566
565251.281	470698.118	3.562
565331.720	470654.359	3.609
565215.784	470680.723	3.495
565261.214	470680.924	3.843
565347.320	470637.736	3.701
565238.168	470646.331	3.504
565267.266	470659.574	3.510
565376.071	470618.099	3.655
565267.658	470606.126	3.482
565291.059	470632.995	3.680
565403.294	470579.806	3.901
565313.766	470613.080	3.736
565438.642	470553.483	4.014
565335.047	470583.508	3.857
565462.015	470545.504	4.019
565324.087	470544.786	3.563
565352.128	470560.210	3.838
565493.010	470516.550	4.078
565342.637	470512.165	3.637
565376.723	470532.003	3.847
565503.096	470495.635	4.187
565371.562	470472.318	3.717

X_COOR	Y_COOR	RL
565512.362	470480.319	4.419
565392.358	470491.641	3.814
565488.842	470470.304	4.196
565403.761	470430.692	3.955
565417.224	470508.205	3.922
565465.814	470489.917	4.114
565428.119	470396.865	3.969
565440.416	470492.968	4.065
565364.430	470367.878	3.717
565398.038	470386.920	3.850
565365.089	470368.217	3.663
565335.002	470342.320	3.619
565329.989	470393.864	3.625
565362.293	470422.998	3.632
565317.523	470365.594	3.511
565318.271	470407.339	3.520
565338.103	470454.931	3.577
565296.632	470385.680	3.559
565275.273	470420.959	3.498
565278.903	470467.908	3.437
565298.757	470513.924	3.519
565260.712	470445.312	3.500
565254.399	470508.758	3.460
565283.876	470535.510	3.474
565240.711	470528.774	3.464
565232.121	470490.050	3.640
565258.664	470582.986	3.518
565225.498	470554.206	3.563
565210.355	470513.223	3.675
565238.625	470618.120	3.504
565204.255	470608.594	3.610
565195.537	470537.838	3.534
565219.563	470656.430	3.515
565184.238	470643.796	3.504
565176.707	470588.555	3.831
565199.654	470684.057	3.505
565171.432	470664.332	3.645
565161.290	470621.125	3.973
565168.942	470719.546	3.432
565149.456	470692.012	3.455
565124.499	470629.597	3.697

X_COOR	Y_COOR	RL
565147.169	470750.775	3.346
565130.162	470701.399	3.520
565107.789	470660.847	3.571
565123.106	470712.938	3.304
565088.406	470693.549	3.745
565113.363	470733.117	3.313
565076.736	470714.971	3.528
565089.282	470694.327	3.946
565066.869	470729.071	3.359
565070.943	470682.533	3.465
565066.986	470679.921	3.352
565035.995	470776.690	3.802
565052.551	470789.713	3.683
565066.273	470635.663	3.400
565076.857	470655.016	3.334
565074.612	470803.947	3.506
565074.732	470619.258	3.387
565099.084	470625.122	3.375
565109.129	470610.456	3.401
565086.361	470599.854	3.450
565004.402	470752.620	3.968
565111.476	470559.698	3.460
564965.306	470723.665	4.182
565121.691	470544.354	3.618
565148.308	470561.383	3.518
565134.157	470518.451	3.517
564987.692	470678.188	3.511
565170.469	470521.843	3.496
565168.616	470479.847	3.480
565202.585	470481.567	3.487
565168.681	470479.912	3.474
565053.345	470594.592	3.639
565227.661	470451.079	3.412
565190.005	470447.437	3.409
565233.370	470425.608	3.455
565089.340	470521.089	3.769
565214.353	470405.055	3.441
565258.853	470392.022	3.433
565110.559	470491.963	3.597
565219.446	470355.186	3.470
565281.200	470362.197	3.439

X_COOR	Y_COOR	RL
565117.360	470457.231	3.605
565294.892	470335.168	3.462
565138.694	470423.898	3.572
565217.962	470324.324	3.475
565278.614	470315.768	3.478
565236.234	470286.895	3.438
565218.889	470291.852	3.474
565192.549	470248.834	3.530
565174.606	470279.233	3.441
565158.874	470245.983	3.586
565112.934	470220.061	3.658
565160.941	470302.861	3.496
565122.992	470306.946	3.483
565095.760	470249.573	3.698
565133.392	470350.470	3.580
565114.557	470321.316	3.742
565067.268	470294.652	3.743
565104.240	470399.424	3.525
565038.043	470331.170	3.635
565093.472	470353.952	3.646
565082.081	470419.256	3.476
565021.257	470353.451	3.639
565068.030	470390.929	3.536
565021.276	470353.626	3.580
565060.681	470465.320	3.578
565036.210	470438.565	3.582
565050.228	470489.311	3.576
565041.167	470489.489	3.867
565042.473	470507.744	3.595
565037.145	470460.023	3.564
565034.545	470412.174	3.518
565046.899	470379.145	3.477
565018.988	470377.363	3.432
565041.163	470368.491	3.429
564885.733	470471.483	3.386
564822.721	470470.148	3.342
564833.065	470481.269	3.500
564895.063	470482.367	3.494
564809.598	470481.668	3.371
564825.455	470505.972	3.277
564845.661	470534.186	3.388

X_COOR	Y_COOR	RL
564866.433	470561.049	3.361
564879.987	470563.511	3.395
564895.155	470600.704	3.434
564892.571	470583.962	3.437
564909.595	470625.926	3.580
564912.364	470615.625	3.663
564926.073	470637.828	3.541
564923.026	470647.137	3.543
564942.126	470665.838	3.530
564925.670	470667.507	3.624
564955.901	470682.472	3.584
564936.620	470887.290	6.315
565000.622	470911.716	6.309
565022.451	470919.659	6.224
565007.028	470913.894	6.289
565051.925	470931.237	6.278
565099.960	470952.456	6.756
565073.376	470927.671	3.489
565070.638	470938.552	6.660
565071.834	470933.435	3.786
565053.675	470904.711	3.770
565070.492	470940.382	6.807
565069.880	470942.339	6.704
565028.452	470882.689	3.749
565002.668	470870.017	3.602
564995.655	470849.315	3.497
565025.112	470915.534	5.160
565075.764	470862.269	3.224
564967.405	470839.610	3.503
565028.384	470894.799	4.325
565052.489	470850.590	3.275
564940.460	470829.292	3.557
565033.966	470874.030	3.660
564910.162	470820.362	3.672
565012.748	470828.878	3.394
564880.570	470810.846	3.806
564997.423	470820.556	3.328
565065.485	470814.103	3.514
564892.015	470788.526	3.727
564978.862	470798.235	3.255
565043.734	470798.936	3.639

X_COOR	Y_COOR	RL
564885.732	470765.167	3.886
565024.289	470783.982	3.873
564963.728	470772.720	3.311
564861.635	470752.634	3.960
564997.376	470766.823	3.660
564943.757	470745.428	3.508
564885.300	470718.366	3.862
564982.066	470749.589	3.961
564923.936	470719.262	3.771
564898.234	470699.508	3.977
564939.377	470719.247	4.264
564948.349	470726.510	4.166
564960.600	470733.862	3.959
564971.038	470743.917	3.868
564993.055	470760.667	4.332
565004.401	470768.079	3.560
565017.822	470778.663	3.719
565034.718	470792.944	3.584
565044.729	470799.903	3.620
565056.826	470806.580	3.613
565066.499	470814.676	3.439
565077.527	470822.372	3.637
565093.205	470835.724	3.561
565100.900	470840.542	3.664
565104.769	470844.034	3.694
565098.226	470861.699	3.831
565089.748	470886.728	1.919
565093.698	470878.145	1.965
565113.995	470948.412	3.823
565122.613	470948.109	3.771
565123.592	470964.880	3.772
565172.461	470949.633	3.901
565158.990	470982.392	3.725
565101.476	470965.324	6.495
565104.067	470985.450	6.402
565111.418	470998.401	6.338
565207.821	470953.542	3.745
565209.548	471013.654	3.865
565209.472	471013.765	3.866