FLOOD FORECASTING AND EARLY WARNING STUDIES FOR PARTS OF BANGLADESH

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

HYDROLOGY

by

MD. MIZANUR RAHMAN

DEPARTMENT OF HYDROLOGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)

DECEMBER, 2010

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Flood Forecasting and Early Warning Studies for Parts of Bangladesh**" in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Department of Hydrology, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out during a period from January 2008 to December 2010 under the supervision of Dr. D.S. Arya, Associate Professor, and Dr. N.K. Goel, Professor, Department of Hydrology, Indian Institute of Technology, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(Md. Mizanur Rahman)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(D.S. Arya)
Supervisor

(N. K. Goel)
Supervisor

Date 23/12/10

The Ph. D. Viva-Voce Examination of **Mr. Md. Mizanur Rahman**, Research Scholar, has been held on 11.7.2011

Signature of Supervisors

Karan Bhatia
Signature of External Examiner 11/7/11.

ABSTRACT

Bangladesh is a flood prone country and extreme floods inundate more than half of the country's landmass almost every year. The country is in the lowest ridge of Hindu Kush Himalayan region, which makes the country hydrologically very diverse, complex, and unique. Economy, environment, ecology, livelihood, and development are affected by devastating floods every year.

Flood Forecasting and Warning Service (FFWS) of Bangladesh was established in 1972 as a permanent entity under Bangladesh Water Development Board (BWDB). Initially co-axial correlations, gauge-to-gauge statistical co-relation relationships, and Muskingum-Cunge routing method were used for forecasting of water levels in advance. Facing different devastating floods, Government of Bangladesh conceptualized that the advancement of the forecasting and warning system can improve the FFWS and accordingly different projects were taken up. Despite the advancement of FFWS, the present flood forecasting and warning system of Bangladesh has the following limitations:

- Limitation in updating the morphometric characterstics of river basins which are needed for modeling the flood forecasting system,
- The Lead-time of 48 hrs is not sufficient for disseminating the information to effect timely response of flood prone communities,
- Improper hydraulic designs in the flood plains due to lack of hydrometric measurement of discharge and stage,
- Limited co-ordination between associated organizations, and
- Absence of feedback from end users with the system.

The lead time in present flood forecasting setup can be improved significantly by introducing the concept of forecasted rainfall in flood forecasting models. Further, the present flood warning system can be improved significantly by people's participation and feedback from the involved communities.

The present study has been taken up with the broad objective to develop the methodology for an improved flood forecasting and warning system suitable for Bangladesh using the web resources available in public domain and recent developments in hydrological modeling and GIS technology. The study involved the use of following methods:

(i) Extraction of river network and catchment boundary using 90m (3-arc second) SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) and GIS (Geographical Information System) application,

(ii) Evaluation of ECMWF (European Centre for Medium-range Weather Forecasts) and TRMM (Tropical Rainfall Measurement Mission) rainfall data for flood studies,

(iii) Development of flood forecasting system using MIKE11 Rainfall-Runoff (NAM: Nedbor-Afstromnings-Model), HD (hydrodynamic), and FF (flood forecasting) modelling and ECMWF data for increasing the lead time and minimizing the forecast errors,

(iv) Estimation of design flood discharge and flood levels using L-moments based methods and different modules of MIKE11,

(v) Assessment of existing early flood warning dissemination system based on literature review, interaction with associated organizations, and feedback from the end users.

The selection of study areas for different objectives of the study was of critical importance as most of the rivers of Bangladesh are international rivers and there are a number of unresolved issues between the associated countries. Hence, the study areas were selected in a way that does not generate any controversy and the departments responsible for maintaining data records are minimum. In addition, the availability of data and particular objective of the study played major role in the selection of study areas.

For development of flood forecasting system, ***Jamuneswari river system*** has been selected as it has a high density of raingauges and its stage and discharge data and the river cross sections at different locations are available. Also the entire catchment of the river lies in Bangladesh. To delineate the river network and catchment boundary of the Jamuneswari river catchment, a study has been conducted over twelve different catchments at different locations in Bangladesh to find out the limitation of 90m SRTM DEM (Shuttle Radar Topographic Mission; Digital Elevation Module) and D8 method of ArcGIS 9.3 software.

Teesta subcatchment in Bangladesh has been used for estimation of design flood discharge and design stage. This approach has been developed using frequency analysis, MIKE11 NAM and HD model and GIS mapping technique.

Flood prone areas of ***Dhobaura and Shibalaya*** sub-districts in Bangladesh have been selected for feedback from endusers to assess the existing early flood warning dissemination system (EFWDS).

Delineation of river network and catchment boundary using 3-arc second SRTM DEM

The 90m SRTM DEM have been used to delineate river networks and to extract Jamuneswari catchments boundary using the D8 method and ArcGIS. While delineating the Jamuneswari catchment, limitation of 90m SRTM DEM in drainage network delineation were observed. This led to an extensive study to determine the limitation of DEM data and the D8 method. Twelve catchments of varying geomorphology were chosen from five hydrological zones of Bangladesh. Basin characteristics such as bifurcation ratio, drainage density and channel slope of the catchments were estimated and analyzed. From this study, it is concluded that, in flat terrains, having a slope flatter then 1:2850, delineation of drainage network must be carried out carefully using the Hydrology tool of ArcGIS software that uses the D8 method for delineation of drainage pattern and catchments. It is also recommended that other techniques excluding D8 method as implemented in ArcGIS, should be experimented with before a general conclusion about the use of SRTM data in flat terrains could be drawn.

Evaluation of ECMWF and TRMM rainfall data for flood studies

Under this study, ECMWF and TRMM daily rainfall data for three locations of Ganges, Brahmaputra, and Meghna (GBM) basins in Bangladesh have been analyzed by statistical visual verification, yes/no-dichotomous verification, and continuous variables verification methods. Bangladesh Meteorological Department (BMD) rainfall data for the years 2004 and 2006 are used as the reference data.

The results of the analysis indicate the potential for use of both ECMWF and TRMM in flood studies. Quantitative precipitation estimates from ECMWF and TRMM may be used for areas where rainfall data are not available or where number of rainfall stations are inadequate. The supremacy of either of the methods of rainfall estimation over the other method could not be established. The ECMWF provides the rainfall data in advance and hence can be used in flood forecasting studies to increase the forecast lead time. The ECMWF forecasted rainfall data have been used in Jamuneswari Flood Forecasting System (JFFS) for augmentation of lead time.

Development of Jamuneswari Flood Forecasting and Warning System (JFFS)

In this study, a Jamuneswari Flood Forecasting System (JFFS) has been developed using MIKE11 NAM, HD and FF model in a study area Jamuneswari catchment in the northwestern part of Bangladesh. The used real time hydrometorological data of the catchment have been analyzed to reduce uncertainties. The effect of uncertainties in flood forecasting has been assessed by comparing efficiency index, coefficient of correlation, volume error, peak error, and peak time error. MIKE11 FF module has been applied to minimize error in the forecasted result.

The 24-, 48-, and 72-hour ECMWF forecasted rainfall data for 2006 have been used in the JFFS for augmentation of lead time of flood forecast in the Jamuneswari catchment area. The results show that with increase in forecast lead-time, the accuracy decreases. For increasing the accuracy of flood forecasted result, the JFFS has then been updated using MIKE11 FF module with observed data. The updated JFFS has produced reliable and satisfactory results. The steps for developing this flood forecasting system are generic and can be used in any geographic condition in the world.

Development of approach for estimation of design flow and stage

A study was conducted in the Teesta subcatchment in Bangladesh for determining design flood flows and corresponding flood stages for different return periods using frequency analysis and MIKE11 model. Different distribution functions of frequency analysis were tested for their goodness of fit. The observed discharge data at Kaunia on the river Teesta was used for estimation of design flood. The Pearson Type III distribution was found best fitted by Kolmogorov-Smirnov, D-index, and L-Moment Diagram Ratio tests and accordingly 25-, 50-, and 100-year return periods design floods were computed. The river network of Teesta River was extracted from SRTM 90m DEM. The river network of Teesta subcatchment was then simulated by MIKE11 NAM and HD model. The resultant time series of river stage was then compared with corresponding observed values. From the model, a stage-discharge relationship (Q-h) curve and respective equation were developed for Kaunia station on the river Teesta. The developed equation determines the corresponding flood stage of estimated flood flow of 25-, 50-, and 100-year return periods. The resulting flows and stages will be useful to design hydraulic structures, prepare flood extent maps, to assess vulnerability of flood damage for different return periods, and provide flood forecasting for early warning of floods. The approach presented would be applicable to similar river basin systems where data are limited and scarce.

Assessment for improvement of existing EFWDS of Bangladesh

Flood Forecasting and Warning Centre (FFWC) was established in 1972. The FFWC developed a comprehensive system for collection, processing, and transmission of data, preparation of flood forecasts and warnings on a daily basis and dissemination of forecasts and warnings to various government and non-government organizations, media groups and other concerned parties over the year. From establishment through present, EFWDS of Bangladesh has been improved under several projects. Despite several advances in flood forecasting system in Bangladesh, the existing system often underperforms because the warning dissemination and response of the end users are unsatisfactory. The present study has been taken up with the objective to critically assess the existing EFWDS of Bangladesh and suggest suitable improvements in this system based on review of literature, interaction with officials of various organizations involved in flood forecasting and dissemination, and interaction with the flood affected people of Dhobaura and Shibalaya sub-districts in Bangladesh. The recommendation for active participation by all related organizations has been made in this study. Two studies have been conducted by surveying the opinion of flood vulnerable communities so that all elements of the EFWDS would provide useful flood warnings to all potential users.

ACKNOWLEDGEMENTS

Apart from personal efforts and steadfastness to work, constant inspiration and encouragement given by a number of individuals served as the driving force in earning this day in my life. To quote them all may be a difficult task but direct and indirect assistance and guidance received is gratefully acknowledged. I would like to express my feelings of gratefulness and submit my acknowledgements for them further in the following lines.

First, I wish to express my sincere appreciation and profound gratitude to Dr. N. K. Goel, Professor and Dr. D. S. Arya, Associate Professor, Department of Hydrology, Indian Institute of Technology, Roorkee for their expert guidance, valuable suggestions, continued encouragement throughout the course of this study and critically examining the thesis write-up.

I express my special thanks to SRC members Prof. Dr. D.K Srivastava, Prof. Dr. M. Perumal, Department of Hydrology and Prof. Dr. Nayan Sharma, Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee for time-to-time suggestion and guidance for the right approach of research problem.

I express my sincere thanks to Prof. Dr. B. S. Mahthur, Prof. Dr. D. C. Shinghal, Prof. Dr. Ranvir Singh, Dr. M.K Jain, Assistant Professor; Department of Hydrology of this Institute for their constant inspiration and numerous valuable suggestions, discussions and insightful, and objective commentary on this study.

My thanks are due to Dr. H. Joshi, Professor and Head, and all Research Scholars, and M. Tech. Trainee Officers of the Department of Hydrology for their help and moral support.

I thank the Director, IIT Roorkee and the Ministry of External Affairs, and ICCR, Government of India for providing scholarship under TCS of Colombo Plan during my Ph.D. work. I am thankful to the Government of People's Republic of Bangladesh for deputing me for this study.

The family atmosphere in the Hydrology Information System Laboratory of Department of Hydrology, IIT Roorkee was helpful in the smooth completion of this work. I sincerely acknowledge the association of Mr. Neeraj K. Sharma, Mr. Amarjeet Singh, Mr. Jamshed Ali, Mr. M.L. Gupta, Mr. D.P. Sharama and Mr. Bhanesh Kashyap of Department of Hydrology.

Special regards to Md. Salim Bhuiyan Director, Flood Forecasting and Processing Circle, Bangladesh Water Development Board (BWDB); Md Saiful Hossain, Executive

Engineer, Flood Forecasting and Warning Centre, BWDB; SM Mahbubur Rahman, Director, Flood Management Division, IWM; SM Shanewaz, Director, Flood Management Division Dhaka Bangladesh and AKM Zeaul Hoque, DHI, Australia for providing data, softwares, related reports and suggestions during my study in Roorkee.

I am thankful to the anonymous reviewers of American Society of Civil Engineering (ASCE), Wiley InterSciences and Springer publications for reviewing parts of the thesis. I heartily acknowledge the software developers of Danish Hydraulic Institute (DHI), and Google Search Engine. Their inventions helped to lift my work to the desired limit.

I acknowledge that the TRMM rainfall estimation data used in this study were acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). I also acknowledge to the Bangladesh Water Development Board (BWDB), Institute of Water Modeling (IWM) and Bangladesh Meteorological Department (BMD) for providing observation data and ECMWF rainfall data under Climate Forecasting Application Network (CFAN) in Bangladesh.

I thank to Dr. Ashish Kumar Mitra, Scientist-F, National Centre for Medium Range Weather Forecasting, Minsitry of Earth Science, Noida, India; Mrs. Mandira Singh Shrestha, Water Resources Specialist, Integrated Water and Hazard Management, ICIMOD, Kathmandu, Nepal; Eng. Mohammad Matiur Rahman (P.Eng), Principal Developer, Adaptation and Impacts Research Division, Environment Canada for their extended cooperation to develop my knowledge and skill in different aspects of my thesis work.

I am grateful to Mr. Nasiruddin U. Khan, Chief Extension Officer, BWDB; Mr. Manzurul Hoque, Field officer, Social Welfare Department, Dhobaura, Mymensingh; Mr. Runu Mia, Secretary, Shibalya Union Parishad, Shibalaya, Manikganj; Mr. Aminul Islam, Secretary, Dhobaura Union Parishad, Dhobaura, Mymensingh and Mr. Titu Nandi, NGO Organizer, World Vision, Dhobaura, Mymensingh, Bangladesh for cooperating to conduct the community level survey in connection with the assessment of existing flood warning system in Bangladesh.

I would like to express my heartiest thanks to *Ms. Murumkar Asmita Ramkrishna*, (Maharastra, India) Research Scholar, Department of Hydrology, IIT Roorkee; Ms. Vidhyshree Misir (British Guyana) Traniee Officer, DOH, IIT Roorkee; Mr. Biswamohan Goswami, Superintending Engineer, DVC, India; Dr. Shibayan Sarkar, Assistant Professor, NERIST, Arunachal, India; Mr. Shatish Kumar D, Assistant Professor, NIT Calicut, India;

Mr. Subrata Haldar, Executive Engineer, West Bengal Irrigation Department, India; Mr. Dinesh Bala, Research Scholar, Department of Civil Engineering, IIT Roorkee, India; Mr. Negash Wagesho, Lecturer, University of Arba Minch, Ethiopia; Mr. Ananda Prashad Dhamy, Divisional Engineer, Dept of Irrigation, Nepal; Biswabandhu. K.C. Hydrogeologist, Dept of Irrigation, Nepal; Ms. Garima Agarwal, Master's Candidate, Rochester Institute of Technology, New York, USA for their cordial cooperation in my work and personal help during my long journey to conduct this research.

I would like to express my gratefulness to my wife *Dr. Shafia Shaheen* for bearing huge pain to run my family affairs with my two beloved daughters *Ms. Rokaiya Nurani Shatadru* and *Ms. Chandrika Nurani Irabotee* besides her tedious public level medical professions in Bangladesh. My thanks are also due to my siblings Mr. M Afzalur Rahman, Mrs. Ferdousi Tamnna, Mrs. Afseri Nighat Shima, and Mr. M Iqbalur Rahman for their moral and emotional support.

At the end, from the core of my heart, I would like to thanks my parents who always prayed for me to almighty Allah. Unfortunately, both of them left this world during this research work. *I dedicate my work related to this research to my* ***parents***.

Md Mizanur Rahman

CONTENTS

CANDIDATE'S DECLARATION ....

ABSTRACT i

ACKNOWLEDGEMENTS vii

CONTENTS xi

LIST OF FIGURES xv

LIST OF TABLES xix

LIST OF ABBREVIATIONS xxi

Chapter 1 - Introduction 1

1.0 General about flood problems in Bangladesh 1

1.1 Present setup of flood forecasting and warning service (FFWS) in Bangladesh 3

1.2 Gaps and possible improvements in the existing setup 3

1.3 Objectives of the study 4

1.4 Thesis layout 4

Chapter 2 - Study Area 7

2.0 Selection of study areas 7

2.1 Jamuneswari river system 7

2.2 Catchments used in analysis of 90m SRTM 90 and the D8 method 9

2.3 Teesta subcatchment for estimation of design flood flow and stage 11

2.4 Area used in case studies of EFWDS 13

2.4.1 Dhobaura area 13

2.4.2 Shibalaya area 14

Chapter 3 - Limitation of 90 m SRTM DEM in Drainage Network Delineation using the D8 Method 17

3.0 Introduction 17

3.1 Description of study area 19

3.2 Data Used 19

3.2.1 DEM data 19

3.2.2 Verification data 19

3.3 Methodology 20

3.4 Results and discussion 21

3.5 Conclusions 33

Chapter 4 - Evaluation of ECMWF and TRMM Rainfall Data for Flood Studies 35
4.0 Introduction 35
4.1 Data used for the study 37
4.2 Methodology of evaluation 40
4.2.1 Visual verification 40
4.2.2 Yes/no-dichotomous verification 41
4.2.3 Continuous variables verification 42
4.3 Data analysis and result discussion 42
4.3.1 Analysis of observed rainfall data 42
4.3.2 ECMWF and TRMM data preparation 46
4.3.3 Evaluation of ECMWF and TRMM rainfall data 48
4.4 Conclusions 55
Chapter 5 - Development of Jamuneswary Flood Forecasting System 57
5.0 Introduction 57
5.1 Data collection and processing for JFFS 57
5.2 Development of JFFS using MIKE11 58
5.2.1 Rainfall-runoff (MIKE11-NAM) module 60
5.2.1.1 Description of NAM model structure 60
5.2.1.2 Data requirements for MIKE11 NAM model 63
5.2.1.3 NAM model setup 64
5.2.1.4 Calibration of NAM parameters 69
5.2.1.5 Validation of NAM model 71
5.2.1.6 Uncertainty in NAM model 71
5.2.2 Hydrodynamic (MIKE11-HD) model 75
5.2.2.1 MIKE11 HD model setup 75
5.2.2.2 Integration of NAM with HD modules 79
5.2.2.3 Calibration of integrated MIKE11 NAM-HD modules 81
5.2.2.4 Validation of integrated model 82
5.2.2.5 Flood forecasting using JFFS with ECMWF input 86
5.2.3 MIKE11-FF module 87
5.2.3.1 Updating of JFFS model 88
5.2.3.2 Updated forecast results 89
5.3 Conclusions 90

Chapter 6 - Estimation of Design Flow and Stage using Frequency Analysis and MIKE11 Modeling **91**

6.0 Introduction 91

6.1 Description of study area and data used 92

6.2 Flood frequency analysis 93

6.3 Modelling using MIKE11 software 96

6.3.1 NAM model setup 99

6.3.2 HD model setup 100

River network 100

River cross sections 101

Boundary conditions 101

Hydrodynamic (HD) parameter 103

6.3.3 Integration of rainfall-runoff (NAM) model with HD model 103

6.3.3 Simulation 103

6.3.4 Comparison of river stages and discharge 104

6.4 Development of rating curve equation 110

6.5 Flood stage computation 111

6.6 Conclusions 111

Chapter 7 - Assessment of Existing Early Flood Warning Dissemination System of Bangladesh **113**

7.0 Introduction 113

7.1 Concept of early flood warning systems 113

7.2 Existing EFWDS in Bangladesh 114

7.2.1 Consolidation and strengthening of flood forecasting and warning services (CSFFWS) 114

7.2.2 Environmental monitoring and information network (EMIN) 115

7.2.3 Community flood information systems (CFIS) 115

7.3 Institutions related with EFWDS in Bangladesh 116

7.4 Case studies 117

7.4.1 Methodology for the case studies 117

7.4.2 Questionnaires 118

7.4.2.1 Bengali version 118

7.4.2.2 English version 119

7.4.3 Analysis of survey results 120

7.5 Conclusions and recommendations 125
Chapter 8 - Conclusions and Recommendation for Further Work 127
8.0 General 127
8.1 Limitation of 90m SRTM DEM in drainage network delineation using D8 method 128
8.2 Evaluation of ECMWF and TRMM rainfall data for flood studies 128
8.3 Development of Jamuneswary flood forecasting system 128
8.4 Estimation of design flow and stage using frequency analysis and MIKE11 modeling. 129
8.5 Assessment of existing early flood warning dissemination system of Bangladesh 130
REFERENCES 131
APPENDIX 4.1 141
APPENDIX 4.2 142
APPENDIX 5.1 143
APPENDIX 5.2 145
APPENDIX 5.3 146
APPENDIX 6.1 147
LIST OF PUBLICATIONS 151

LIST OF FIGURES

Figure 1.1: Area affected and crop damage during major floods events since 1950 2

Figure 2.1: Jamuneswari river system along with rainfall, evaporation, discharge, and water level stations. 8

Figure 2.2: Location of various catchments having used in analysis of 90m SRTM DEM and the D8 method 10

Figure 2.3: Teesta river subcatchment used in the study 12

Figure 2.4: Dhobaura area 14

Figure 2.5: Shibalaya area 15

Figure 3.1: Flow diagram of the methodology adopted for delineation of stream network using SRTM DEM. 20

Figure 3.2 a: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Upper Tangon (matching) 22

Figure 3.2 b: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Upper Karatoya (matching) 23

Figure 3.2 c: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):TulshiGanga (not matching) 24

Figure 3.2 d: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Chitra (not matching) 25

Figure 3.2 e: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Sib River (not matching) 25

Figure 3.2 f: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Matamuhuri (matching) 26

Figure 3.2 g: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Banar (not matching) 27

Figure 3.2 h: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Sangu (matching) 27

Figure 3.2 i: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB): Someswari (matching) 28

Figure 3.2 j: Delineated catchments (green colour for delineated and red colour for reference data obtained from BWDB): Kushiara (not matching) 28

Figure 3.2 k: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB): Kushiara (not matching) 28

Figure 3.3a: Comparison of the delineated river network of the Jamuneswari catchment with Google Earth images (Blue is the delineated and Yellow is that extracted from Google Earth) 29

Figure 3.3b. Comparison of the delineated river network of the Jamuneswari catchment with BWDB digital river network (Blue is the delineated and Yellow is the BWDB digital river network) 30

Figure 3.4: Comparison of mean absolute error with the catchment slope. The figure clearly shows that the error is increasing significantly with the increase in slope. 32

Figure 4.1: The map shows the GBM basin. The location of the three rainfall stations selected in GBM basins lying in Bangladesh are also shown with red color. 36

Figure 4.2: Time series of daily rainfall data observed by BWDB and BMD. 43

Figure 4.3: Time series of monthly rainfall data observed by BWDB and BMD. 44

Figure 4.4: Comparison of CDF of observed rainfall of BWDB and BMD. 46

Figure 4.5: Time Series Plots of BMD observed (black line), ECMWF (red dotted), and TRMM (blue dash) daily rainfall data 49

Figure 4.6: Bar chart of BMD observed, ECMWF, and TRMM monthly rainfall data 50

Figure 4.7: Histogram of relative frequency of rainfall distribution of BMD observed, TRMM and ECMWF daily RF data 51

Figure 4.8: Comparison of CDF among BMD observed, ECMWF, and TRMMM daily RF data. 52

Figure 5.1: Flow chart for development of flood forecasting system 59

Figure 5.2 Structure of the NAM model used in JFFS 61

Figure 5.3: Jamuneswari catchment has been divided in two parts as Catch-1 (upper catchment) in the north and Catch-2 (lower catchment) in the south. 65

Figure 5.4: Thiessen polygons of different rainfall stations 66

Figure 5.5: Thiessen polygons of evapotranspiration stations 69

Figure 5.6: Time series and scatter plots of model result versus observed data 74

Figure 5.7: River network of MIKE11 HD model 76

Figure 5.8: Cross section of Jamuneswari river at chainage 126.00 km 79

Figure 5.9: Time series (a) and scatter plot (b) of model versus observed discharge at Chak-Rahimpur (chainage 53 km of river Karatoya) 83

Figure 5.10: Time series and scatter plots of model versus observed river stgaes at Chak-Rahimpur 84

Figure 5.11: Time series and scatter plots of 24-, 48-, and 72-hour early forecasting by JFFS 86

Figure 5.12: Graphical representation of Nash Sutcliffe's efficiency index and coefficient of correlation. 87

Figure 5.13: Graphical representation of peak time error and the slope of the 45^0 line of scatter plot 87

Figure 5.14: Conceptual flowchart of simulation period of forecasting procedure. 88

Figure 6.1: Flow diagram of MIKE11 NAM and HD models simulation for preparing rating curve 97

Figure 6.2: River network used in HD model 100

Figure 6.3: Representative cross section of the River Teesta at Kaunia chainage 79.79 km 101

Figure 6.4: Longitudinal Profile of River Teesta (Chainage 13610 m to 121000 m), Jamuna (Chainage 8000m to 84500 m) and Old-Brahmaputra (Chainage 0 m to 31000 m) 102

Figure 6.5: Model generated inflow (Jamuna at 37,750m, Teesta at 45,845m, and Ghagot at 134,135m) and outflow (Old-Brahmaputra at 26,000m and Jamuna at 81,100m) from May 1996 to November 2003. 104

Figure 6.6: Model generated inflow (Jamuna at 37,750 m, Teesta at 45,845 m, and Ghagot at 134,135 m) and outflow (Old-Brahmaputra at 26,000 m and Jamuna at 81,100 m) for 2001. 105

Figure 6.7: Graphical comparison of model results with the observed river stage at Chilmari (chainage 36,100 meter on river Jamuna) from May 1996 to November 2003. 107

Figure 6.8: XY plot of model river stage vs observed river stage considering monsoon period at Chilmari 108

Figure 6.9: Graphical comparison of model results. Solid line represents simulated discharges (30 minutes time step) and the squares represents observed (low frequency and irregular time steps) discharge data at Kaunia for monsoon period only. 109

Figure 7.1: Feedback from affected people about media of warning dissemination conducted by NGO during 2000-2002 under CSFFWS 114

Figure 7.2: Occupation of respondents. 120

Figure 7.3: Vulnerability statistics of life and properties. 121

Figure 7.4: Response (in %) of respondent in favour of warning message dissemination.... 122

Figure 7.5: Response about suitable mass media for dissemination of warning message 124

LIST OF TABLES

Table 1.1: Some notable flood events after independence of Bangladesh and their impact 2

Table 3.1: Comparison of river network delineation for different catchments 31

Table 4.1: Contingency table for yes/ no dichotomous method 41

Table 4.2: Statistical comparison of BMD and BWDB observed rainfall data...................... 45

Table 4.3: Comparison of the extracted time series of ECMWF RF data by different methods with the BMD observation.. 47

Table 4.4: Evaluation of ECMWF and TRMM daily rainfall data with BMD observed rainfall data using yes/no dichotomous verification method 53

Table 4.5: Evaluation of ECMWF and TRMM daily RF time series by continuous variables verification methods 54

Table 5.1: Area and weightage of rainfall Thiessen polygons of JFFS catchments............... 67

Table 5.2: Rearrangement of weightage of rainfall thiessen area of Catch-1 and Catch-2..... 68

Table 5.3: Area and weightage of evaporation thiessen area of Catch-1 and Catch-2........... 68

Tabel 5.4: Calibrated values of mostly affected NAM model parameters. 70

Table 5.5: Results of the validated NAM model 74

Table 5.6: Detail of river network connection.. 77

Table 5.7: Integration of subcatchments for lateral flows in the river channel 80

Table 5.8: Initial water depth for different river reach 81

Table 5.9: Different values of Manning's 'M' or 'n' at different chainage of rivers. 82

Table 5.10: Results for model discharges at Chak-Rahimpur after adding the HD model with the calibrated NAM model 84

Table 5.11 Improvement of result integrating HD module along with NAM module 85

Table 5.12: Quantitative difference of uncertainty among the 24-, 48-, and 72-hour early forecasted by JFFS... 87

Table 5.13: Comparison of the results before and after updating by MIKE11-FF module..... 89

Table 5.14: Updated forecast result for 24-, 48-, and 72-hour lead-time 89

Table 6.1: Summary of randomness and stationary test result 94

Table 6.2: Summary of design floods for 25-, 50-, and 100-year return periods based on different distribtutions. 95

Table 6.3: Statistical parameter for comparison of model results for through out the full year 107

Table 6.4: Statistical parameter for comparison of model result for monsoon period only...109

Table 7.1: Response of local people about the causes of flood in their area 120

Table 7.2: Response statistics of dissemination of present warning message by FFWC 121

Table 7.3: Response in % in favour of different proposed format for *flood depth* warning message dissemination 122

Table 7.4: Response in % in favour of different proposed formats for *flood extent* warning message dissemination 123

Table 7.5: Response in favour of the institutions or organizations to disseminate the warning message to the end users. 124

Table 7.6. Response in favour of the institutions or organizations to respond for disaster management according to warning message to the end users. 125

LIST OF ABBREVIATIONS

Symbols		Description
AD	:	Advection Dispersion
ADB	:	Asian Development Bank
BBS	:	Bangladesh Bureau of Statistics
BDPC	:	Bangladesh Disaster Prepardness Centre
BMD	:	Bangladesh Meteorological Department
BWDB	:	Bangladesh Water Development Board
CDF	:	Cumulative Distribution Function
CEGIS	:	Centre of Environmental Geographical Information System
CFAN	:	Climate Forecasting Application Network
CFIS	:	Community Flood Information System
CGIAR	:	Consultative Group for International Agriculture Research
CSFFWS	:	Consolidation and Strengthening of Flood Forecasting and Warning Service
CSI	:	Consortium for Spatial Information
CZ	:	Central Zone
DA	:	Data Assimilation
DEM	:	Digital Elevation Model
DEMON	:	Digital Elevation Model Network
DHI	:	Danish Hydraulic Institute
DMB	:	Disaster Management Bureau
DOH	:	Department of Hydrology
ECMWF	:	Europen Centre for Medium-range Weather Forecasts
EFWDS	:	Early Flood Warning Dissemination System
EFWS	:	Early Flood Warning System
EMIN	:	Environmental Monitoring and Information Network
ESRI	:	Environment Systems Research Institute
FEH	:	Flood Estimation Handbook
FF	:	Flood Forecasting
FFS	:	Flood Forecasting System
FFWC	:	Flood Forecasting and Warning Centre
FFWS	:	Flood Forecasting and Warning Service
GBM	:	Ganges Brahmaputra and Meghna

GIS	:	Geographical Information System
GoB	:	Government of Bangladesh
GPCP	:	Global Precipitation Climatology Project
HD	:	Hydrodynamic
IFSAR	:	Interferometric Synthetic Aperture Radar
IIT	:	Indian Institute of Technology
ISDR	:	International Strategy for Disaster Reduction
JFFS	:	Jaumuneswari Flood Forecasting System
JICA	:	Japan International Cooperation Agency
MFDM	:	Ministry of Food and Disaster Management
MoWR	:	Ministry of Water Resources
MSU	:	Michigan State University
NAM	:	Nedbor Afstromnings – Model
NASA	:	National Aeronautics and Space Administration
NCEP	:	National Centre for Environment Protection
NED	:	National Elevation Data
NEZ	:	Northwestern Zone
NGO	:	Non-Government Organisation
NOAA	:	National Oceanic and Atmospheric Administration
NWZ	:	Northwestern Zone
ODA	:	Official Development Assistance
RF	:	Rainfall
RR	:	Rainfall – Runoff
SEZ	:	Southwestern Zone
SMS	:	Short Message Service
SRTM	:	Shuttle Radar Topography Mission
ST	:	Sediment Transport
TMPA	:	TRMM – Multi-Satellite Precipitation Analysis
ToF	:	Time of Forecast
TRMM	:	Tropical Rainfall Measurement Mission
TV	:	Television
UHM	:	Unit Hydrograph Module
UNDP	:	United Nations Development Programme
USGS	:	United States Geological Survey
WARPO	:	Water Resources Planning Organization
WMO	:	World Meteorological Organization

1.0 General about flood problems in Bangladesh

Bangladesh is a flood prone country and extreme floods inundate more than half of the country's landmass almost every year. The country is in the lowest ridge of Hindu Kush Himalayan region, which makes the country hydrologically very diverse, complex and unique (Chowdhury and Wards, 2004; Sikka and Ringler 2009). Economy, environment, ecology, livelihood and development are affected by devastating floods every year.

The country contains the confluence of the Ganges, Brahmaputra and Meghna rivers and their crisscrossed tributaries as well distributaries, which discharge into the Bay of Bengal. Heavy rainfall over the catchment of these rivers can produce up to 8 to 10 m depth of flooding (Alam, 2000). Land is mainly flat, with 40 percent of its landmass upto 10 meters above mean sea level (Rahman et al., 2010).

Climate of Bangladesh is tropical influenced by the Himalayan Mountains in the north and northeast, and by the Bay of Bengal in the south. High monsoon rains associated with Bangladesh's unique geographical location in the delta of the world's largest river basin make it extremely vulnerable to recurring floods. Agriculture is the dominant land use in the country covering about 59 percent of the land whereas rivers and other water bodies constitute about 9 percent (BBS, 2002). Country has experienced seven highly damaging floods in the 20th century. Since independence in 1971, Bangladesh has experienced floods of a vast magnitude in 1974, 1987, 1988, 1998, and 2004 (FFWC, 2005a). Impacts in terms of affected area, estimated economic loss (only direct losses from damage of crop, infrastructures like roads, railways, embankments, bridges etc.) and deaths of human beings during these severe floods are presented in Table 1.1. The area affected and crop damage during major flood events of the country since 1950 are presented in Figure 1.1 (Hossain, 2004).

The largest recorded flood (both in terms of depth and duration of flooding) in Bangladesh occurred in 1998 when about 68 percent of the country was under water for several months.

Various structural measures such as flood embankments, channel improvements, river training works and coastal embankments and nonstructural measures such as flood plain zoning, and flood forecasting and early warning systems have been adopted in the country to minimize the flood losses.

Table 1.1: Some notable flood events after independence of Bangladesh and their impact

Event	Impact			Source
	Inundated area (in term of % of the country's geographical area of 144000 km^2)	No. of human deaths	Estimated damages	
1974 flood	36	Over 2,000 deaths, followed by famine with over 30,000 deaths	Not recorded	FFWC (2005b)
1987 flood	40	Over 2055 deaths	Approximately US$ 1.0 billion	The World Bank (2002)
1988 flood	61	Persons affected 45 million, 2300 deaths	Approximately US$ 1.2 billion	The World Bank (2002)
1998 flood	68	Persons affected 31 million, 1100 deaths	Damaged 500,000 homes, 23,500 km roads and 4500 km embankment, crop damage 500,000 ha, damage worth about US$ 2.8 billion	The World Bank (2002)
2004 flood	38	Persons affected 36 million, 750 deaths,	Damaged 58,000 km roads and 3,100 km embankment, crop damage 1.3 million ha, damage worth about US$ 2.2 billion	ADB-World Bank (2004)

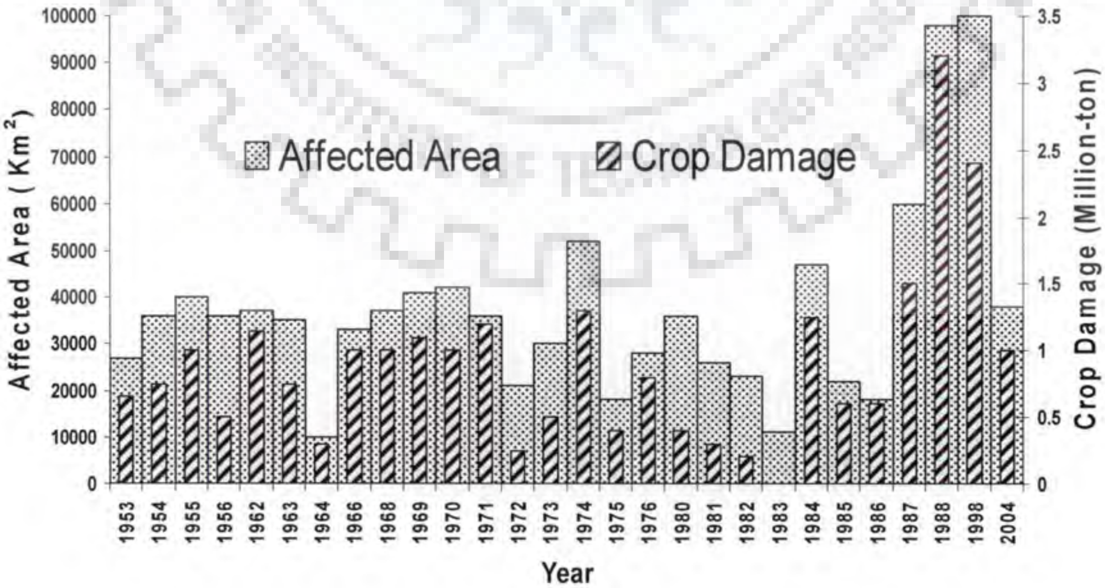


Figure 1.1: Area affected and crop damage during major floods events since 1950

1.1 Present setup of flood forecasting and warning service (FFWS) in Bangladesh

Flood Forecasting and Warning Service (FFWS) of Bangladesh was established in 1972 as a permanent entity under Bangladesh Water Development Board (BWDB). Initially co-axial correlations, gauge-to-gauge statistical co-relation relationships and Muskingum-Cunge routing method were used for forecasting of water levels. During that period, only 10 water level stations on the major river systems were installed and all the computations were done manually. In 1981, World Meteorological Organization (WMO) and United Nations Development Programme (UNDP) provided technical assistance for computerization of the hydrological database.

Facing the devastating floods of 1987 and 1988, it was conceptualized that the integrated hydro-informatics and geo-informatics based forecasts should be introduced. MIKE11 model was installed at the Flood Forecasting and Warning Centre (FFWC) during 1990-91. Amid the devastation of the 1998 flood, BWD realized that the further improvement of the FFWS was needed, thence a new project entitled "Consolidation and Strengthening of Flood Forecasting and Warning Services" was implemented in Cooperation with Danida during 2000-2004. The present maximum lead time is 48 hours for most of the rivers.

1.2 Gaps and possible improvements in the existing setup

The present flood forecasting and warning system of Bangladesh has the following limitations:

- Limitation in updating the morphometric characterstics of river basins which are needed for modeling the flood forecasting system,
- The Lead-time of 48 hrs is not sufficient for disseminating the information to effect timely response of flood prone communities,
- Improper hydraylic designs in the flood plains due to lack of hydrometric measurement of discharge and stage,
- Limited coordination between associated organizations, and
- Absence of feedback from end users with the system.

The lead time in present flood forecasting setup can be improved significantly by introducing the concept of forecasted rainfall in flood forecasting models. Further, the present flood warning system can be improved significantly by people's participation and feedback from the involved communities.

1.3 Objectives of the study

The present study has been taken up with the broad objective to develop the methodology for improved flood forecasting and warning system suitable for Bangladesh, where availability of hydrometeorological data is very limited, using the web resources available in public domain and recent developments in hydrological modeling and GIS technology. The study involved the use of following methods:

1. Extraction of river network and catchment boundary using 3-arc second SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) and GIS (Geographical Information System) application,

2. Evaluation of statistics of ECMWF (European Centre for Medium-range Weather Forecasts) and TRMM (Tropical Rainfall Measurement Mission) rainfall data for flood studies,

3. Development of flood forecasting system using MIKE11 Rainfall-Runoff ((NAM: Nedbor-Afstromnings-Model), HD (hydrodynamic), and FF (flood forecasting) modelling and ECMWF data for increasing the lead time and minimizing the forecast errors,

4. Estimation of design flood discharge and flood levels using L-moments based methods and different modules of MIKE11,

5. Assessment of existing early flood warning dissemination system based on literature review, interaction with associated organizations and feedback from the end users.

1.4 Thesis layout

The thesis has been arranged in eight chapters. Flooding problems in Bangladesh, broad objectives of the study and layout of the thesis are explained in Chapter 1. The details of various study areas have been provided in Chapter 2.

Chapter 3 provides the details of extraction of the river network and catchment boundaries using 90m (3arc second) SRTM DEM and GIS. The limitations of SRTM 90m DEM and D8 method of ArcGIS software are also described in this chapter.

Statistics of ECMWF and TRMM rainfall data have been evaluated in Chapter 4. The visual, dichotomous and continuous variable verification methods are used to evaluate the data with the observed data. This chapter discusses the potentiality of these two data sets in forecasting and estimation of flood flows.

Chapter 5 develops the flood forecasting system using MIKE11 rainfall runoff (NAM) and hydrodynamic (HD) model in the Jaumuneswari catchment and the developed system is named as JFFS. Chapter 6 describes the development of the approach to estimate the flood flow and stage using frequency analysis and MIKE11 NAM and HD moduls in Teesta sub-basin in Bangladesh.

Chapter 7 describes the assessment of the existing early flood warning dissemination system in Bangladesh. Recommendations to improve the system have been made on the basis of review of literature, discussions with the officials of departments involved in flood forecasting and warning dissemination and interaction with the end users i.e., people of the flood affected areas of Dhobaura and Shibalaya sub-districts in Bangladesh. The thesis ends up with conclusions and recommendations for further work in Chapter 8.

2.0 Selection of study areas

The selection of study areas for different objectives of the study was of critical importance as most of the rivers of Bangladesh are international rivers and there are number of unresolved issues between the associated countries. Hence, the study areas have been selected in the way that does not generate any controversy and the departments responsible for maintaining data records are minimum. In addition, the availability of data and particular objective of the study played major role in the selection of study areas.

For development of flood forecasting system, ***Jamuneswari river system*** has been selected as it has a high density of raingauges its stage and discharge data and cross sections at different locations are available. Also the entire catchment of the river lies in Bangladesh. To delineate the river network and catchment boundary of the Jamuneswari river catchment, a study has been conducted over twelve different catchments at different locations in Bangladesh to find out the limitation of 90m SRTM DEM (Shuttle Radar Topographic Mission; Digital Elevation Module) and D8 method of ArcGIS 9.3 software.

Teesta subcatchment in Bangladesh has been used for estimation of design flood discharge and design stage. This approach has been developed using frequency analysis, MIKE 11 NAM and HD model and GIS mapping technique.

Flood prone areas of ***Dhobaura and Shibalaya*** sub-districts in Bangladesh have been selected for assessment of existing Early Flood Warning Dissemination System (EFWDS) of Bangladesh.

2.1 Jamuneswari river system

The Jamuneswari river system covers a catchment area of 2593 km^2, spanning between 88.047° E to 89.036° E longitudes and 24.056° N to 26.020° N latitudes as shown in Figure 2.1.

Jamuneswari river system includes six rivers (namely Charalkata-Jamuneswari, Bullai, Chikli, Kala, Akhira, and Karatoya) and all the rivers originate in Bangladesh with a total length of 366.60 km. The runoff in the area is generated due to local rainfall, which sometimes can be very intense and may cause severe floods in the area.

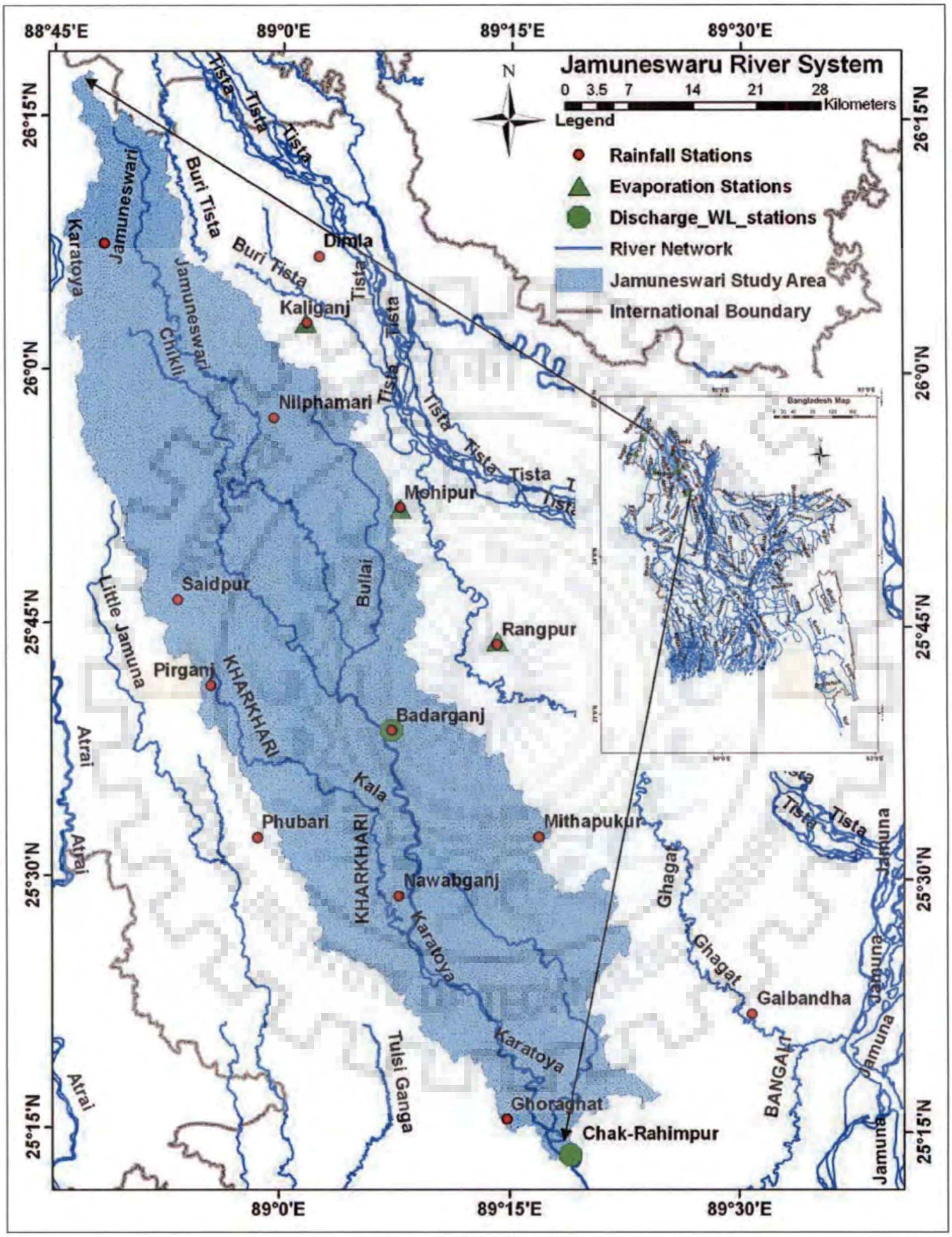


Figure 2.1: Jamuneswari river system along with rainfall, evaporation, discharge, and water level stations.

The Jamuneswari river system can be divided into two sub-regions. The Northern sub-region is the Himalayan Piedmont Plains (ODA and JICA, 1993), which consists of steep ground slope of 1:4500 and highly permeable soil. The topography of the southern (lower) sub-region is flat having a slope of 1:10000 and soil is less permeable.

The Charalkata-Jamuneswari (C.Jamuneswari) river originates from an in-country small catchment. The C.Jamuneswari-Karatoya is the main river system draining the catchment. Other minor rivers in the region are the Bullai, Chikli, Kala, and Akhira. The Bullai, Chickly, and Kala meet C.Jamuneswari. C.Jamuneswari is renamed as Karatoya from it chainage at 144.00 km. Flow of Akhira meets river Karatoya at Ghoraghat. Finally, this C.Jamuneswari-Karatoya meets Bangali river near Mohimaganj.

Most of the rivers of this region flow from very steep to flat ground. A quick response of flash floods occur in the upper portion of the region which inundates both banks of the rivers. The flood cells and depression areas in the lower portion act as flood retention reservoirs.

2.2 Catchments used in analysis of 90m SRTM 90 and the D8 method

A total of twelve catchments namely Matamuhuri-Upper, Tulshi-Ganga, Tangon-Upper, Karatoya, Sangu-Upper, Jamuneswari, Kushiara, Garai-Madhumati-Kaliganga, Chitra, Sib, Someswari, and Banar River were chosen to analyze the delineation accuracy of 90 m SRTM DEM and the D8 method. The location of these catchments are shown in Figure 2.2 in gray shades color.

The guiding criteria for selection of the catchments are slope, drainage density and proximity to the rivers. It is worth mentioning here that Bangladesh is divided into five hydrological zones viz., Northeastern Zone (NEZ), Northwestern Zone (NWZ), Central Zone (CZ), Southeastern Zone (SEZ), and Southwestern Zone (SWZ). The NEZ has hilly terrain and is located in the hydrological region of world's highest rainfall intensity causing frequent flash floods in the region. The slope of this zone suddenly becomes very flat (roughly 1:10000 to 1:20000) when it reaches the plain land immediately after hilly terrain. The NWZ is located in the non-hilly terrain having moderately steeper slope than all other plain lands of Bangladesh. Often floods are observed in this NWZ. The SEZ is located in the hilly as well as coastal plain land.

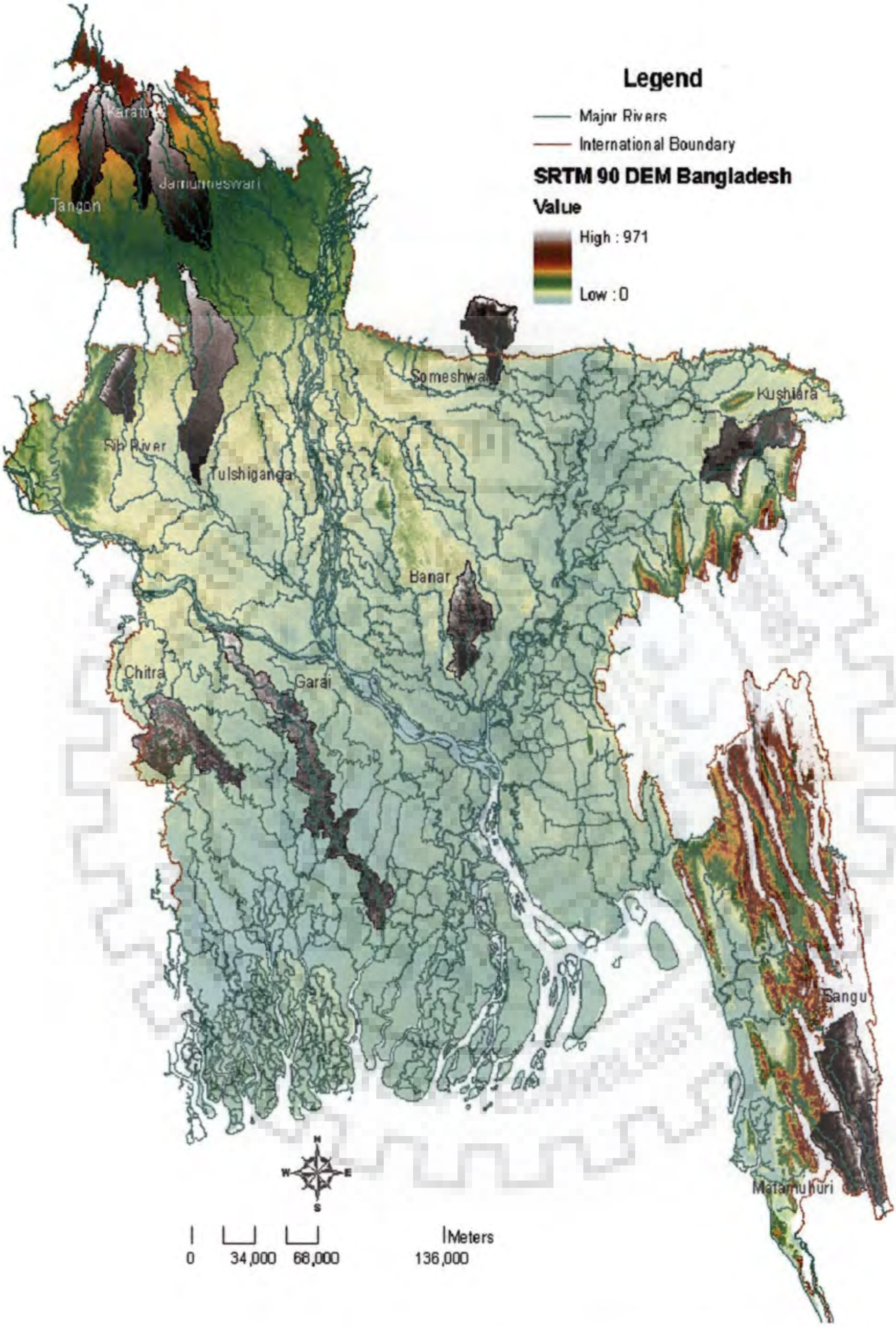


Figure 2.2: Location of various catchments having used in analysis of 90m SRTM DEM and the D8 method

The river network causes both the storm surge and flash flood in this zone. The SWZ is coastal plain land of Ganges Delta without any hilly terrain. The tidal rivers cause storm surge due to cyclone in this SWZ. The CZ is mainly the flood plain of three major rivers, namely, Ganges, Brahmaputra, and Meghna. The land pattern is comparatively low-lying, through which all the floods water pass towards the Bay of Bengal. The representative catchments has been chosen as follows: Kushiara and Someswari from NEZ; Tangon-Upper, Karatoya, Jamuneswari, Sib, and Tulshi-Ganga have from NWZ; Matamuhuri-Upper and Sangu-Upper from SEZ; Garai-Madhumati-Kaliganga, and Chitra from SWZ; and Banar from CZ.

2.3 Teesta subcatchment for estimation of design flood flow and stage

The Teesta River originates from the Himalayas in Sikkim state of India. It flows approximately 180 km through a mountainous area before entering into the alluvial plains of Northwestern part of Bangladesh. It keeps flowing in a braided course for a length of 96 km before crossing the India-Bangladesh border. After traveling 121 kilometers, it joins the Jamuna River near Chilmari in Bangladesh (Figure 2.3).

The Brahmaputra (total length 2700 km) originated from Chemayung-Dung glacier near Manassarowar and Mount Kailas. In Bangladesh, this river is named as Brahmaputra up to Bahdurabad (71 km) and Bahdarubad to Aricha it is named as Jamuna (205 km). The Brahmaputra-Jamuna is one of the largest rivers in the world, which flows through Tibet, China, India, and Bangladesh. The earthquake and catastrophic flood in 1787 changed the main course of Brahmaputra near Bahadurabad. It passes towards south through Serajganj District to confluence with the Ganges at Aricha. The original Brahmaputra is now flowing towards southeast, passes through Jamalpur, Mymensingh, and Kishorgonj district to confluence with the Upper-Meghna near Bhairabbazar and is known as "Old-Brahmaputra". The main course of the Brahmaputra is now known as river Jamuna, it carries an average discharge of 4000 m^3/sec water in the monsoon, and experienced maximum discharge of 98600 m^3/sec in August 1998. Ghagot is a short length river, originated inside Bangladesh and confluences with Jamuna. The adjoining river systems bypasses excess flow into Jamuna through this river. The Dharla river is also flashy in nature, enters into Bangladesh at Talukshimulbari from India and confluences with Jamuna at Gujimari.

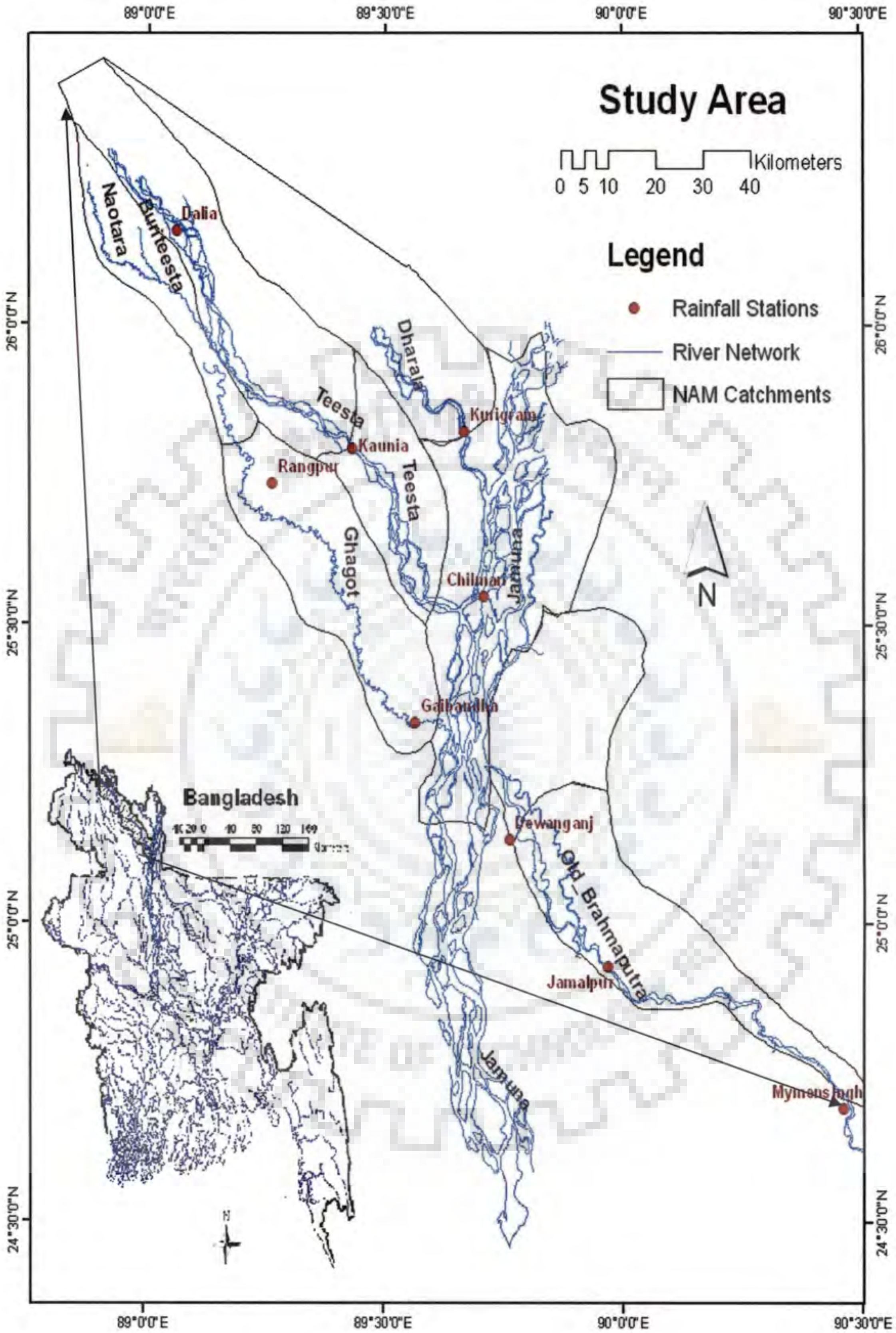


Figure 2.3: Teesta river subcatchment used in the study

The area of Teesta subcatchment in Bangladesh is about 2000 km^2. The riverbed is comprised of fine to medium sand common to alluvial flood plain. This area is classified as shallow depressions and valleys of moribund river channels formed by long morphological history of changes in the river courses. The general slope of the river varies from 0.47 to 0.55 m/km. The Teesta subcatchment is vulnerable to flooding in each year. There are two main tributaries of the river Teesta namely, Naotara and Buri-Teesta. Flash floods are caused by the Teesta River and if the peaks are observed in rivers Jamuna and Teesta simultaneously, the worst flood situation occurs in the area. In this study, only the Bangladesh portion of the Teesta subcatchment has been considered for analysis.

The region has an average annual rainfall of 1900 mm. Maximum temperature ranges from 25°C in January to 35°C in April/May. Evapotranspiration reaches to a maximum in April when temperature, sunshine, and wind are all close to their maxima (ODA and JICA, 1993).

2.4 Area used in case studies of EFWDS

Two case studies for Dhobaura and Shibalaya areas have been conducted for incorporating the feedback of local communities in the EFWDS.

2.4.1 Dhobaura area

Dhobaura sub-district is located at latitude: 25°5' N and longitude: 90°31' E (Figure 2.4) under Mymensingh District in the northern part of Bangladesh. The total area of Dhobaura Upazila is 251.05 km^2. The Nitai and Kongsho rivers control the hydrology of Dhobaura. These rivers originate from Meghalaya hill tracts and cause frequent and high magnitude flash floods in the flat terrain in Dhobaura immediately after steep hill slopes. The area is characterized as heavy rainfall area. The area is in the vicinity of the Cherapunji (Latitude: 25° 18' N, Longitude: 91° 42' E), Assam, India.

Dhobaura is vulnerable to flash floods caused by intensive rainfall in upstream hilly catchments. During flash floods, water level rises quickly and the areas are flooded rapidly. Flash floods cause extensive damage to agriculture, infrastructure, and culture fisheries. Homesteads close to the main river channel are also subject to erosion during flash floods. At present, there is no Early Flood Warning System in Dhobaura and adjacent areas.

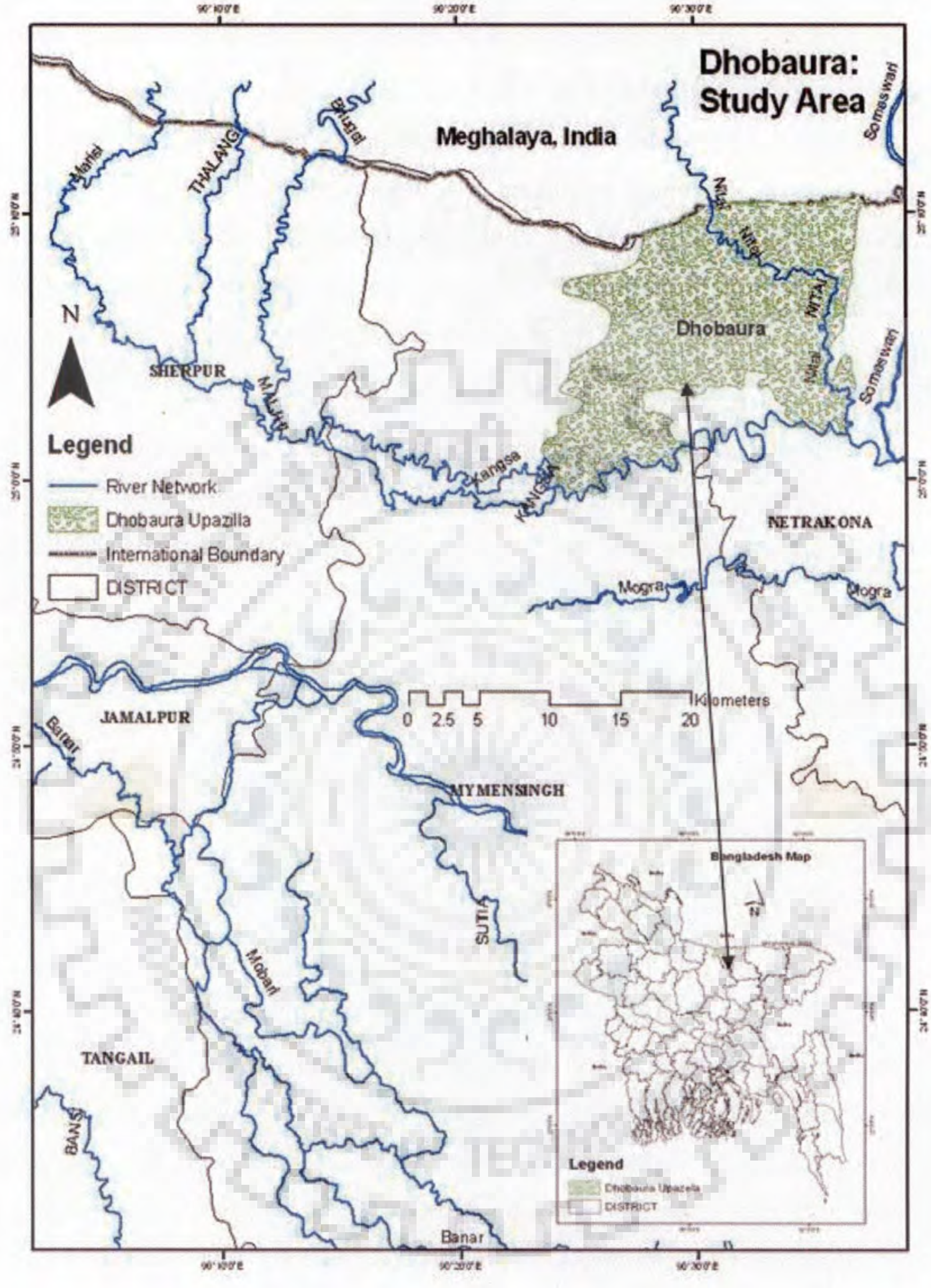


Figure 2.4: Dhobaura area

2.4.2 Shibalaya area

Shibalaya subdistrict is located at latitude: 23°50′ N and longitude: 89°47′ E (Figure 2.5) under Manikganj district in the central part of Bangladesh, has an area of 199 km^2. The area is vulnerable to flooding as most of the land is low lying.

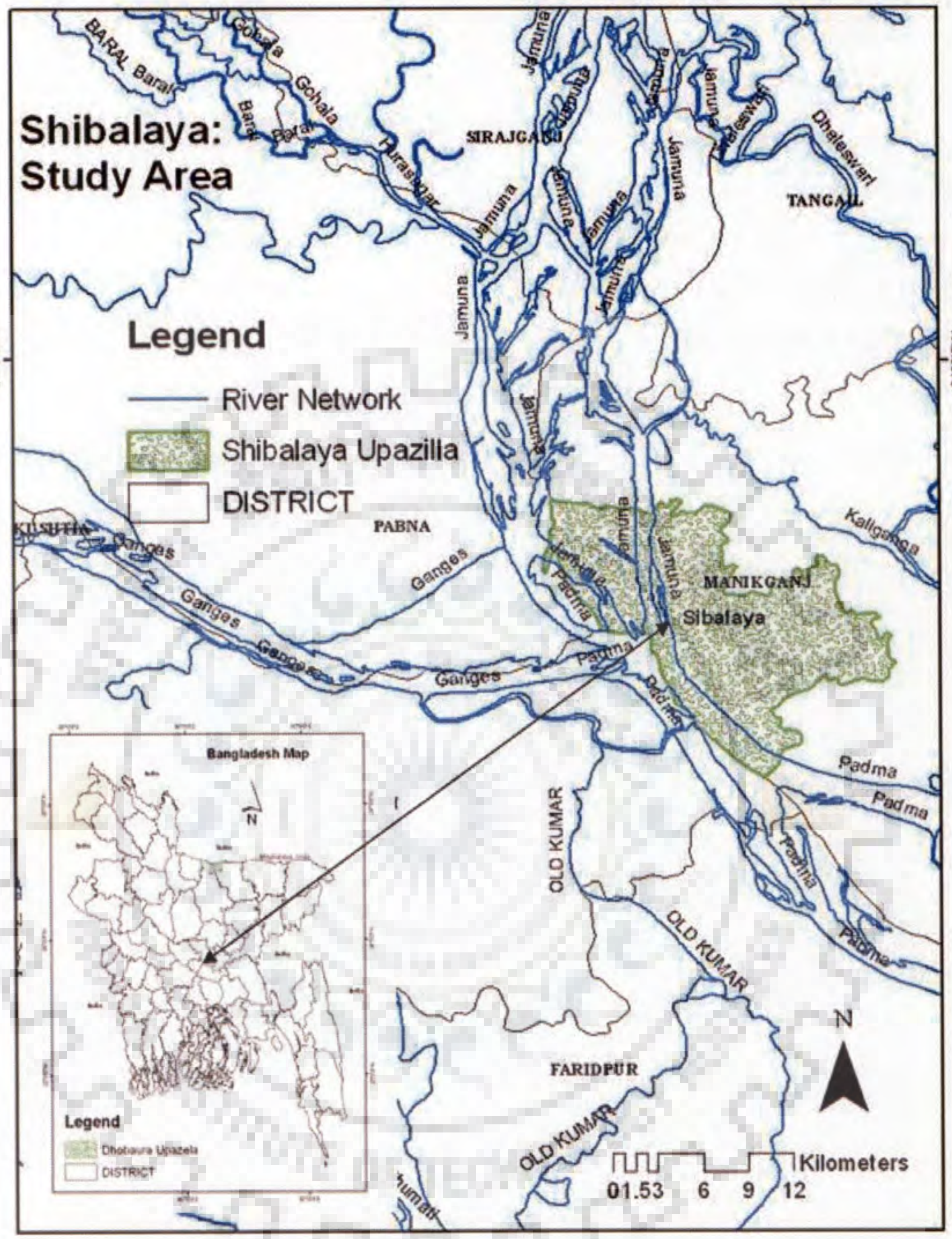


Figure 2.5: Shibalaya area

The central part of Bangladesh is highly vulnerable to floods caused by over bank flow from the Brahmaputra-Jamuna River. Shibalaya is one of the most vulnerable areas, and floods result in significant damages to crops and livelihoods as experienced in 1998 and 2004.

Floods and erosion cause damage to crops, infrastructure, culture fisheries and homesteads. Floods in Shibalaya are influenced by flows in three rivers: the Ganges, Jamuna, and Padma. At present, Shibalaya does not have any EFWS. The onset of flood is severe when the Ganges and Brahmaputra face high peak as well as flood recession is slow because of backwater pressure by the river Padma due to spring tide or depression in the Bay of Bengal. As indicated in section 2.1, the limitation of 90m SRTM DEM and D8 method of ArcGIS 9.3 software was critically examined before delineation of the river network and catchment boundary of Jamuneswary river catchment. The details of this study are described in Chapter 3.

Chapter 3 - Limitation of 90 m SRTM DEM in Drainage Network Delineation using the D8 Method

3.0 Introduction

In recent years, digital elevation model (DEM) data derived from remote sensing data have widely been used in delineation of river network and catchment boundaries. NASA (National Aeronautics and Space Administration) is providing 90m (3-arc second) DEMs for about 80% of the globe (CGIAR-CSI, 2008) under the program Shuttle Radar Topographic Mission (SRTM). The mission provides near-global topographic coverage of the Earth's surface with unprecedented consistency and accuracy, which is widely used for large-scale hydrologic studies (Bhang and Schwartz, 2008). The DEM data is available in public domain on the website of the Consortium for Spatial Information (CSI) of the Consultative Group for International Agriculture Research (CGIAR) (http://srtm.csi.cgiar.org).

In hydrological studies, DEMs are often used for delineation of drainage network, catchment boundary and in estimation of various catchment parameters such as slope, contours, aspects etc. The accuracy of typical geomorphological and hydrological descriptors (e.g., stream networks, watershed areas, slope, aspect, etc.) in a rugged terrain were examined with the 90m SRTM DEM data set which indicates that stream networks and watersheds can be easily identified accurately (Hancock et al., 2006).

Alarcon and O'Hara (2006) conducted a research where Interferometric Synthetic Aperture Radar (IFSAR) and 30m SRTM DEM data were used to delineate a portion of the Saint Louis Bay watershed (Mississippi). In addition to these, two digital elevation databases, the National Elevation Data (NED) and the United States Geological Services' Digital Elevation Model (USGS-DEM) were also used for delineation. They found that 30m SRTM DEM produced optimum delineation results comparable to NED when areas and sub-basin perimeters were compared.

The computation for DEM pixels are based on the flow routing model introduced by O' Callaghan and Mark (1984) and referred as D8 Method. In this D8 method, each pixel discharges in to one of its eight neighbors in direction of steepest descent. In the beginning this method was problematic when grid cells lacking a down slope neighbor occurred in the DEM referred to as a "sink", resulted in flow paths that terminated at the grid cell with the lowest elevation, producing a discontinuous drainage pattern. Jensen and Domingue (1988) developed a new procedure to eliminate all "sinks" prior to the assignment of flow directions. This method is being widely used in ESRI products ArcView, ArcGIS, and Arc Info and established in Arc Hydro (Maidment, 2002).

The D8 approach has limitation arising from the discretization of flow into only one of eight possible directions, separated by 45° (Fairfield and Leymarie, 1991; Quinn et al., 1991). Moore and Grayson (1991) pointed out that D8 method allows flow which originates over a two dimensional pixel is treated as a point source (non-dimensional) and is projected down slope by a line (one dimensional). Costa-Cabral and Burges (1994) also pointed out that the flow direction in each pixel is restricted to eight possibilities. Costa-Cabral and Burges (1994) then developed a new approach named digital elevation model network (DEMON), having advantage like contour based models (Moore et al., 1988), represents varying flow width over nonplanar topography. Tarboton (1997) described that the best fit plane cannot pass through only four corner elevations, which may be inconsistent or counterintuitive flow directions that are a problem in DEMON.

Tarboton (1997) developed a new procedure based on representing flow direction as a single angle taken as the steepest downward slope on the eight triangular facets centered at each pixel. He demanded that different methods give different results and differences increases with the increases of resolution of DEM and argued that his method is simple and effective approach. Orlandini et al. (2003) described the method proposed by Tarboton (1997) as a reasonable compromise between the simplicity of the D8 method and the sophistication introduced in more recent formulations to improve the precision with which drainage directions are resolved by the D8 method. He also mentioned that a certain degree of dispersion is maintained by Tarboton's method.

Orlandini et al. (2003) proposed path-based methods for the determination of nondispersive drainage directions in grid-based digital elevation models. The path-based methods extend the descriptive capabilities of the classical D8 method by cumulating the deviations between selected and theoretical drainage directions along the drainage paths. It can not eliminate the bias at the local level, but provides nonlocally constrained drainage paths which may improve significantly the nondispersive description of drainage systems. Orlandini et al. (2003) also gave reasons of this bias which affect in the field of terrain analysis applied to geomorphology and hydrology. Seibert and McGlynn (2007) proposed new triangular multiple flow direction algorithm (MD ∞) which combines the advantages of the multiple flow direction algorithm as proposed by Quinn et al. (1991) with the use of triangular facets as in the approach described by Tarboton (1997).

Thus, many researchers sought to improve the D8 method proposed by O'Callaghan and Mark (1984) but the same has since been traditionally used in ESRI GIS software (ArcView, ArcGIS, Arclnfo) as well as in Arc Hydro. This study is also concerned with this traditional D8 method and findings may be related with methods' uncertainty or morphological characteristics of used DEM. The findings may be changed with respect to change of software or resolution of DEM.

However, while conducting a hydrological study of river Jamuneswari in Bangladesh, it has been found that the river network have been poorly delineated using the the popular and widely used GIS software ArcGIS (version 9.3) that uses the D8 method for determination of the network when the result compared with Google Earth images and observed network received from Bangladesh Water Development Board (BWDB). This has led to an extensive study to determine the limitations of use of 90m SRTM DEM in hydrological applications using ArcGIS 9.3 for flat terrain, especially in Bangladesh.

3.1 Description of study area

Please refer Chapter 2 for description of study area.

3.2 Data Used

3.2.1 DEM data

Three arc-second (90m) SRTM digital elevation model data (Version-3 and Version-4) for twelve catchments (namely, Matamuhuri-Upper, Tulshi-Ganga, Tangon-Upper, Karatoya, Sangu-Upper, Jamuneswari, Kushiara, Garai-Madhumati-Kaliganga, Chitra, Sib, Someswari, and Banar river, detail given in Chapter 2) have been used in this study. The data sets have been downloaded from the CGIAR website (http://srtm.csi.cgiar.org/).

3.2.2 Verification data

Two types of reference data have been used to verify the results as given below:

I. Google Earth images (Google Inc., 2008).

II. Bangladesh Water Development Board's (BWDB) data: BWDB digitized river network (having more than 100 m width) using SPOT multi spectral images (scale 1:50,000) of 1989, topographic maps from Survey of Bangladesh of 1: 50,000 scale (1961) and LANDSAT TM (Thematic Mapper) images 1997 (WARPO, 2008).

3.3 Methodology

The stream networks for each river catchment have been delineated using the Hydrology tool of Spatial Analyst extension of ArcGIS 9.3 (ESRI, 2007) by filling the sinks, finding the flow direction, estimating the flow accumulation, delineating the stream line and watershed. The flow directions are determined by identifying the neighboring cells which has the highest positive distance weighted drop (Jensen and Dominique, 1988). Flow accumulation is determined as the sum of the flow accumulation values of the neighboring cells which flow into it (Venkatachalam et. al, 2001). The stream order is also defined using Strahler's classification (Strahler, 1952). A step-by-step methodology used for drainage network delineation is shown in Figure 3.1.

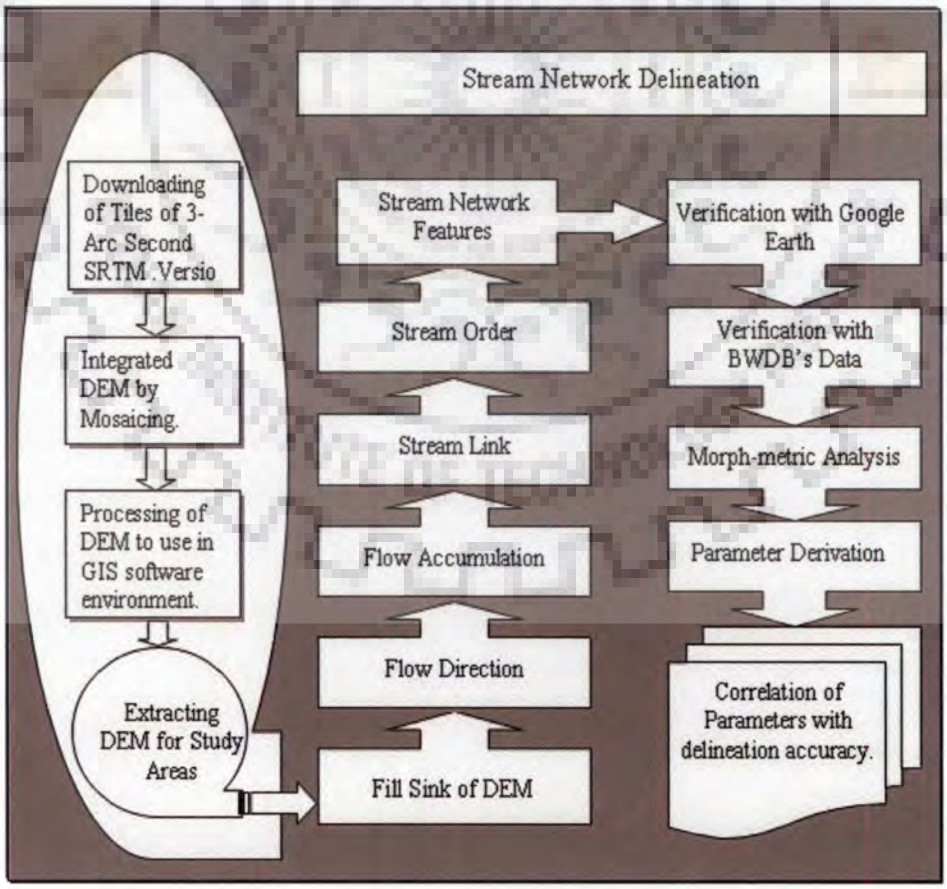


Figure 3.1: Flow diagram of the methodology adopted for delineation of stream network using SRTM DEM.

The delineated drainage pattern and the watersheds have then been compared with the BWDB data and further verified by exporting the data to Google Earth. Other catchment parameters like slope, bifurcation ratio, width of the river, and drainage density have also been estimated in order to study the effect on river network delineation.

The distance between delineated river network and BWDB's observed network have been measured in a number of equal intervals using ArcGIS 9.3. The interval has been taken as less than 1 km for each catchment. This measured distance is the alignment error in river network delineation in both right (considered as +Ve) and left side (considered as –Ve) of the original river network. The mean absolute error (MAE) and standard deviation have been computed for quantification of the error in network alignment. MAE has been preferred because absolute error measures are less dominated by a small number of large errors and thus it is a more reliable indicator of typical error magnitudes (Lettenmaier and Wood, 1993). The equation to calculate MAE is

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|O(x_i y_i) - D(x_i y_i)\right| \qquad \text{----------- (3.1)}$$

Where,

$O(x_i y_i)$ = location of observed river alignment at the rate of i^{th} interval,

$D(x_i y_i)$ = location of delineated river network at the rate of i^{th} interval, and

N = total number of interval

3.4 Results and discussion

The drainage network and watersheds have been delineated following the methodology as described above. All delineated catchments are shown in Figures 3.2a to 3.2k.

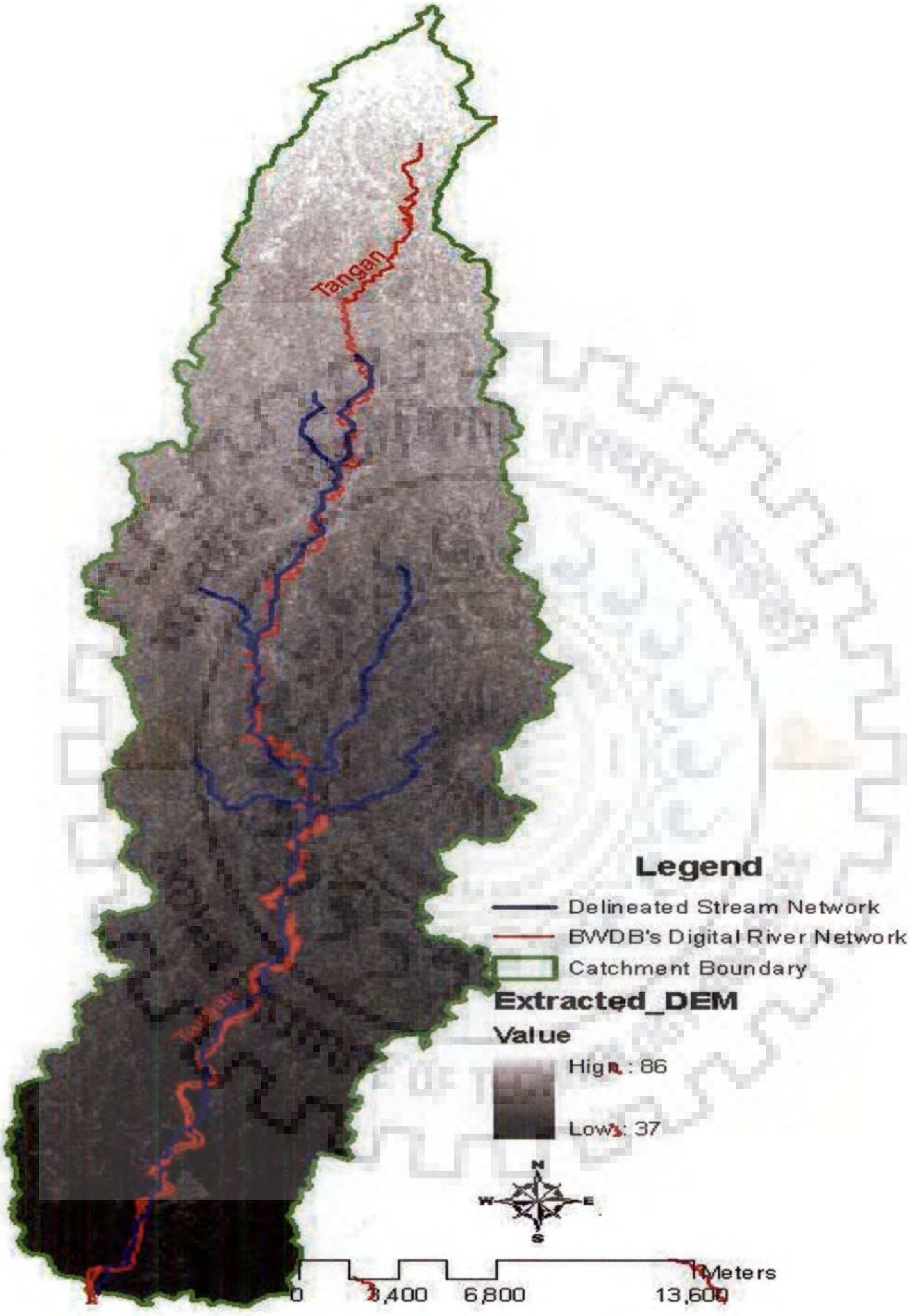


Figure 3.2 a: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Upper Tangon (matching)

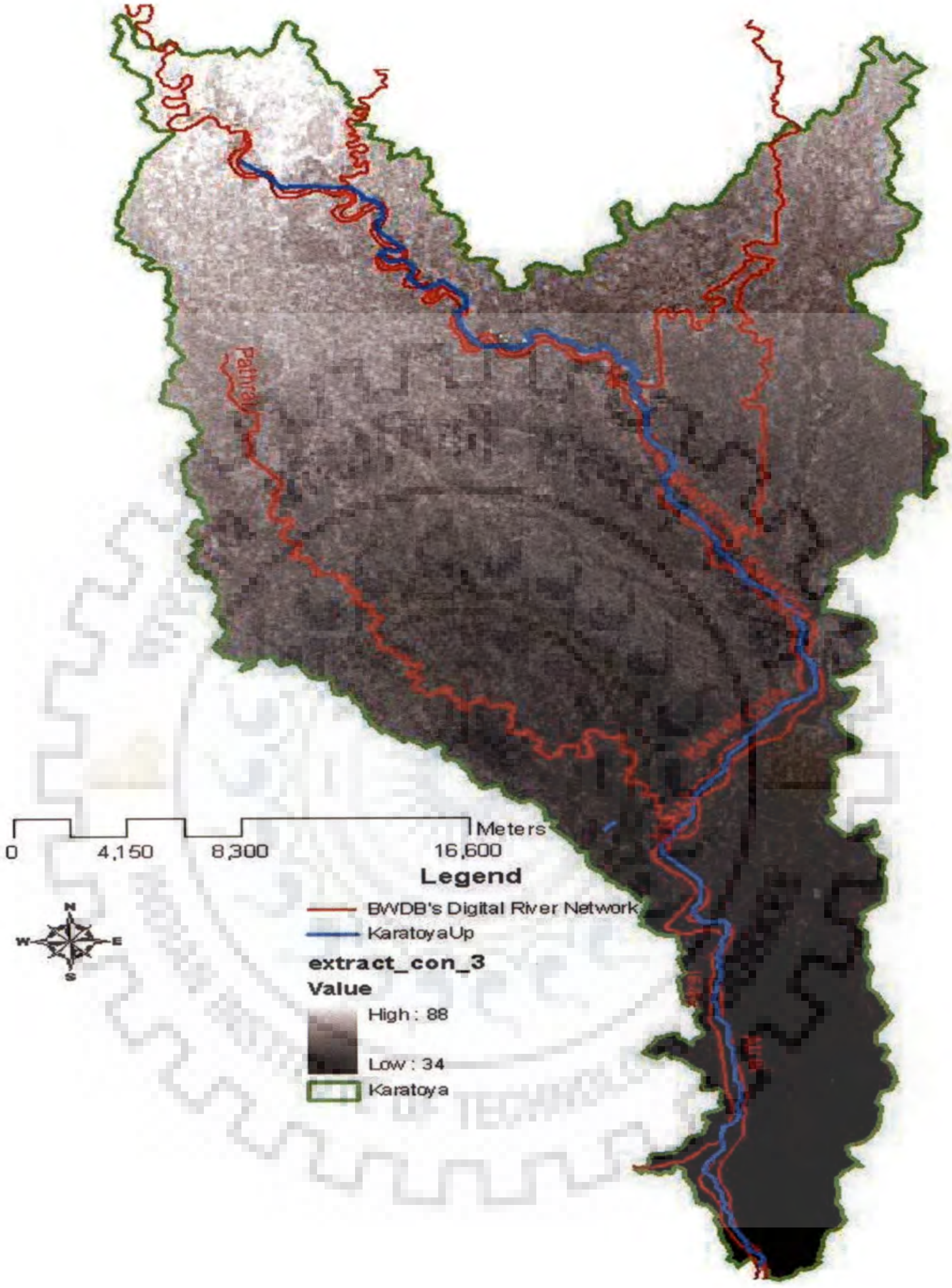


Figure 3.2 b: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Upper Karatoya (matching)

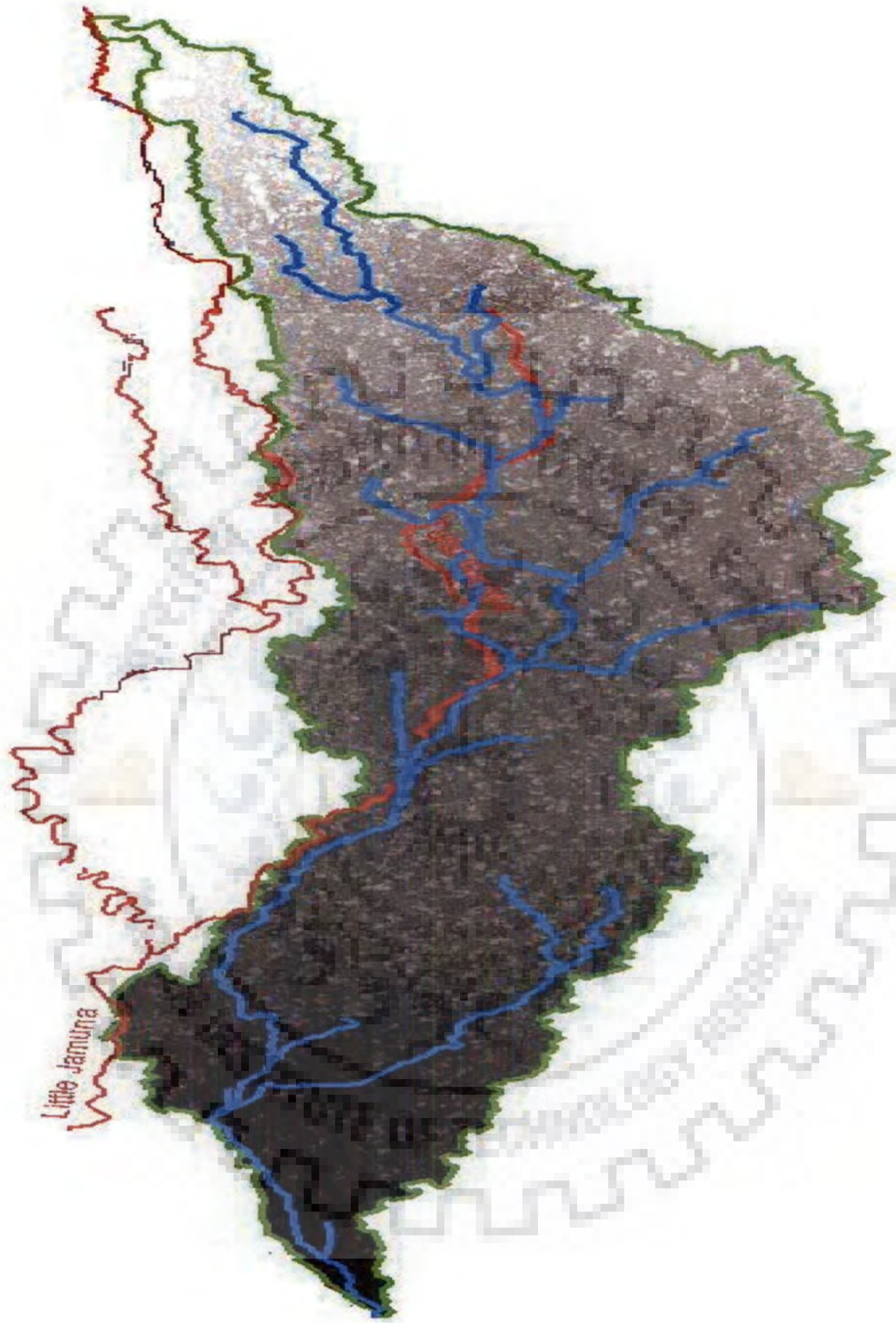


Figure 3.2 c: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):TulshiGanga (not matching)

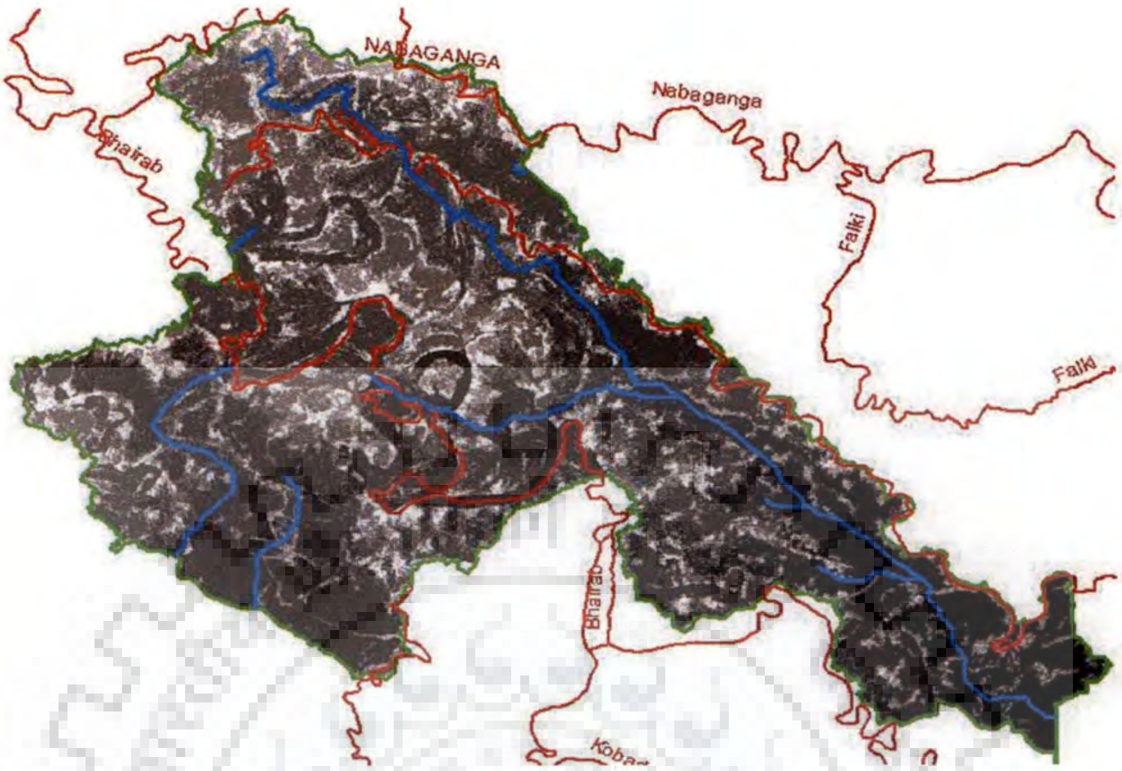


Figure 3.2 d: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Chitra (not matching)

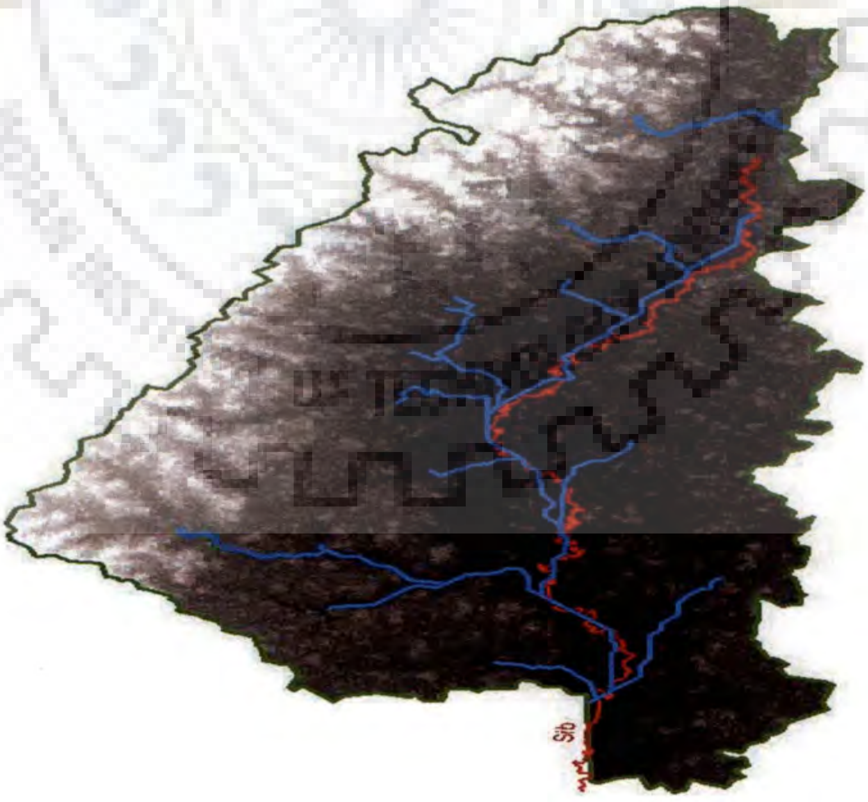


Figure 3.2 e: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Sib River (not matching)

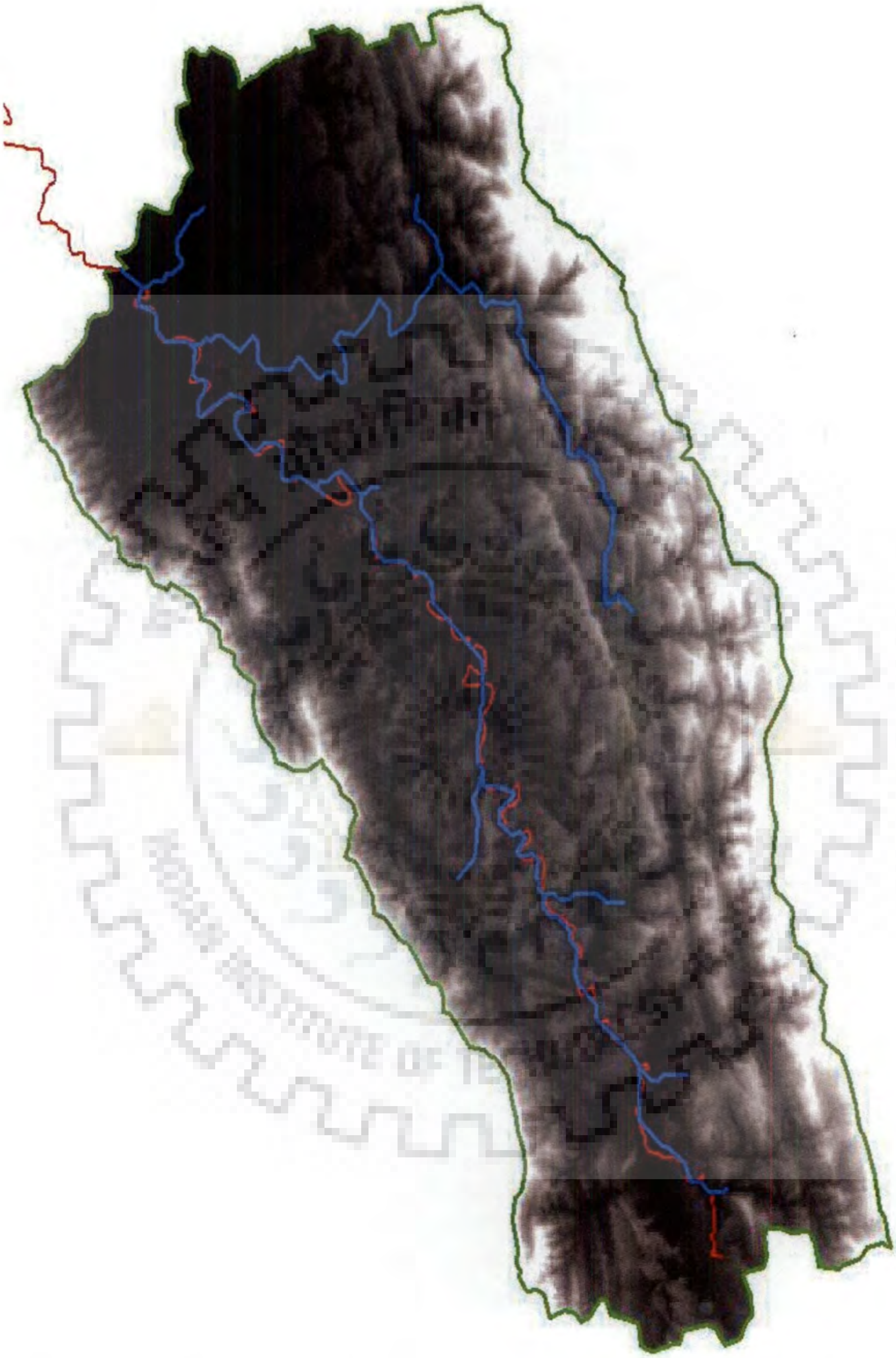


Figure 3.2 f: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Matamuhuri (matching)

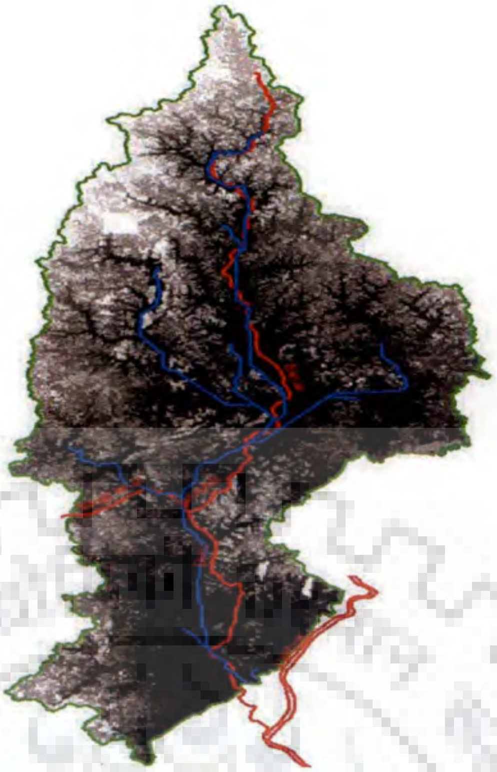


Figure 3.2 g: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Banar (not matching)

Figure 3.2 h: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB):Sangu (matching)

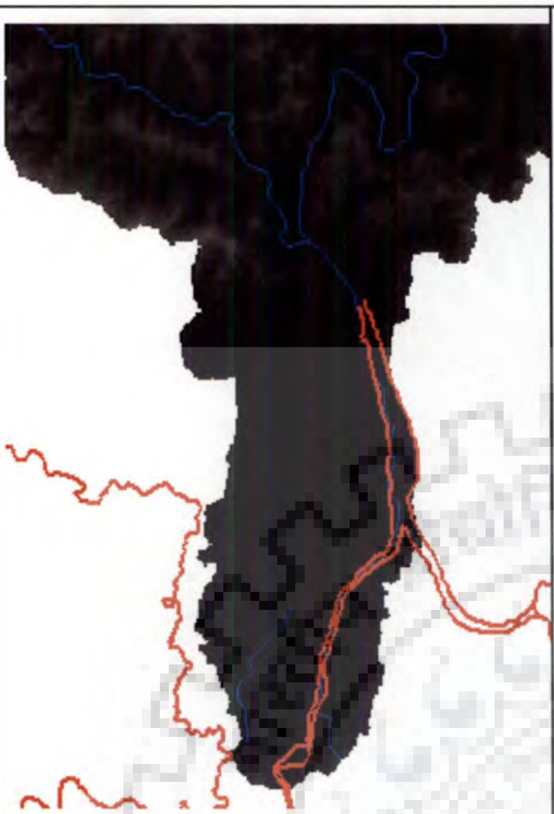


Figure 3.2 i: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB): Someswari (matching)

Figure 3.2 j: Delineated catchments (green colour for delineated and red colour for reference data obtained from BWDB): Kushiara (not matching)

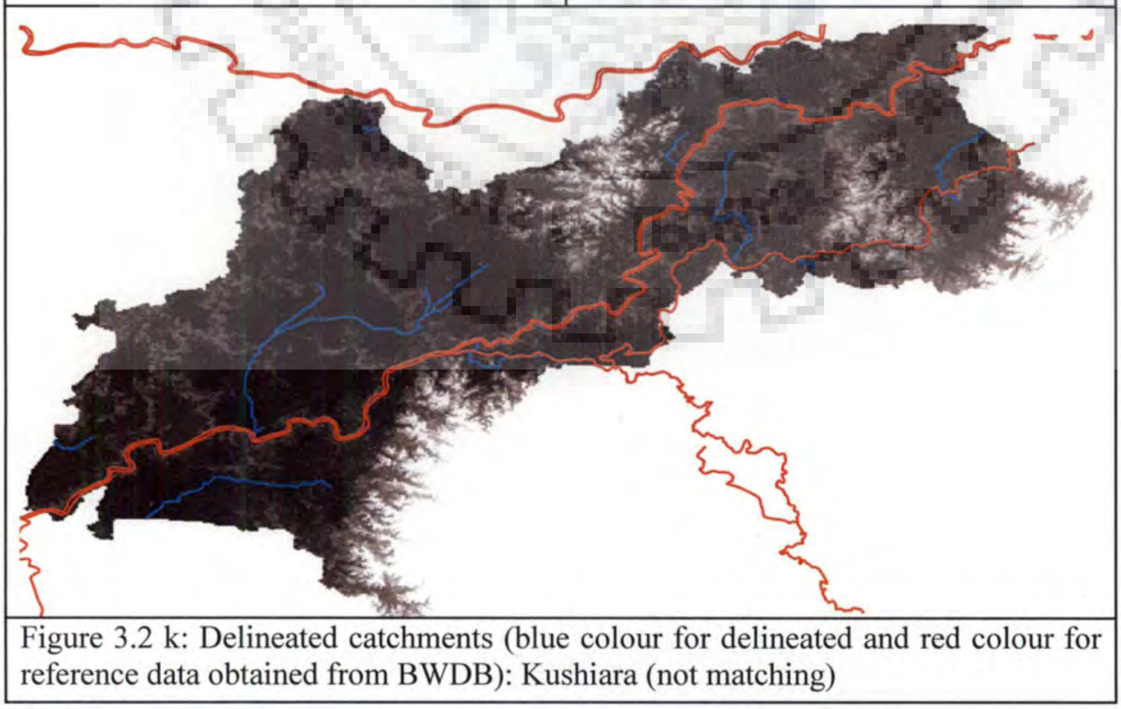


Figure 3.2 k: Delineated catchments (blue colour for delineated and red colour for reference data obtained from BWDB): Kushiara (not matching)

Drainage network of the Jamuneswari River is shown in Figure 3.3. The delineated network and BWDB network have been overlaid and presented in Figure 3.3a. The figure shows that the BWDB drainage network follows the rivers/stream network as seen in Google Earth images and the delineated network deviates significantly from the streams. Delineated networks along with the BWDB drainage network is also provided in Figure 3.3b which clearly shows the deviations in network delineation.

Figure 3.3a: Comparison of the delineated river network of the Jamuneswari catchment with Google Earth images (Blue is the delineated and Yellow is that extracted from Google Earth)

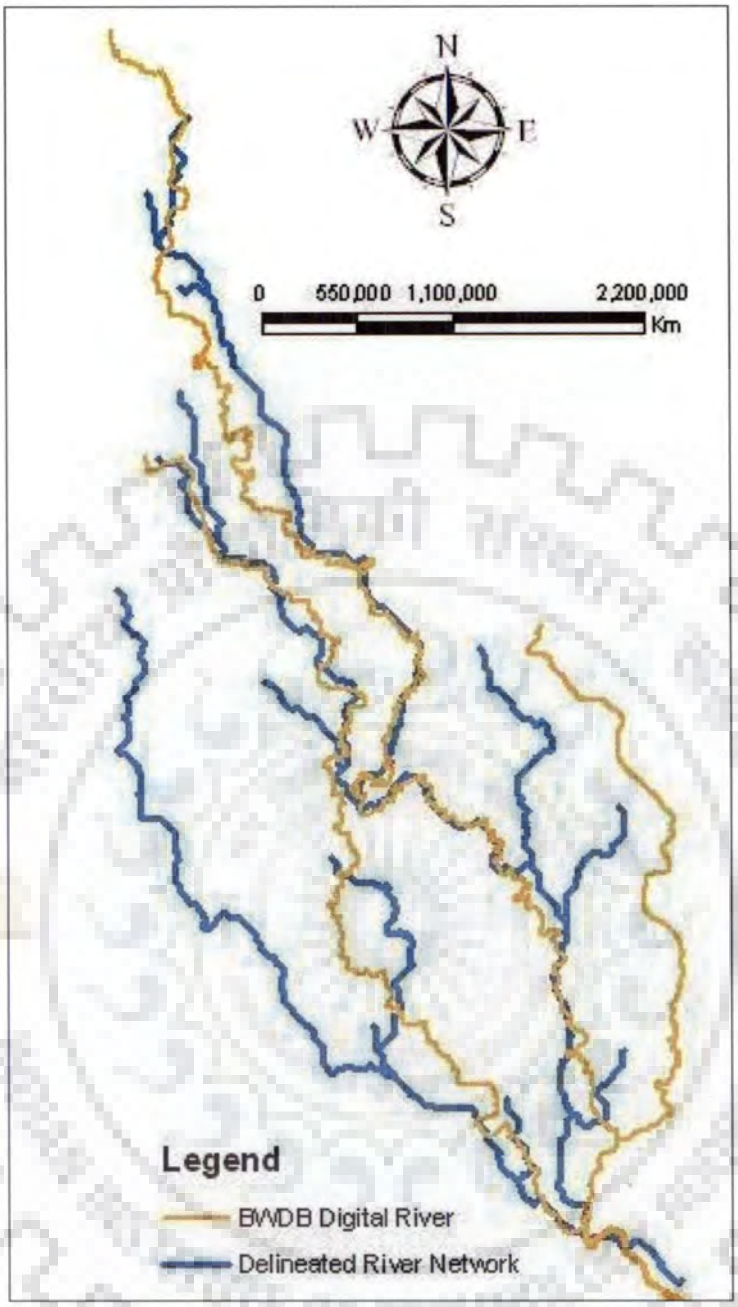


Figure 3.3b. Comparison of the delineated river network of the Jamuneswari catchment with BWDB digital river network (Blue is the delineated and Yellow is the BWDB digital river network)

The range of deviation is from 0 m to 5000 m for all the catchment. A catchment is classified as matching when the minimum deviation is zero and maximum deviation is less than 500 m. The same analysis has been done for all catchments and the results are presented in Table 3.1.

Geomorphological parameters namely the bifurcation ratio (Rb), drainage density (Dd), and channel slope (Sc) of the 12 catchments have been estimated to find if there exist any relationship between the geomorphological parameters and suitability of the 90m SRTM DEM data for automatic delineation of drainage network using hydrology tool of ArcGIS.

Table 3.1: Comparison of river network delineation for different catchments

River Name	*Slope of the River Bed**	*Bifurcation Ratio, Rd*	*Average Width of the River (in m)**	*Drainage Density, D_d (Total Length, ∑L, & Area, A)*	*Deviation of the Alignment*	*Remarks*
01	02	03	04	05	06	07
Matamuhuri Upper	1:500	Rd =3.25	200 to 300 =250	D_d =0.15 (∑L=97 km, Area=658 km²)	Matches (max. 322m deviation, no breaking of stream line exists)	Slope ≤1:2850
Tangon Upper	1:2000	Rd =7.00	200 to 700 = 450	D_d =0.15 (∑L=92 km Area=669 km²)	Matches (max. 500m deviation, no breaking of stream line exists)	Slope ≤ 1:2850
Sangu Upper	1:1000	Rd = 3.17	300 to 1000=625	D_d =0.16 (∑L=238 km Area=1535 km²)	Matches (max. 500m deviation, no breaking of stream line exists)	Slope ≤ 1:2850
Karatoya	1:2600	Rd =3.25	> 50 to 450 =250	D_d =0.10 (∑L=92 km Area=954 km²)	Matches (max. 300m deviation, no breaking of stream line exists)	Slope ≤ 1:2850
Someswari	1: 2850	Rd = 2.50	250 to 550 =400	D_d =0.18 (∑L=122 km Area=665 km²)	Matches (max. 200m deviation, no breaking of stream line exists)	Slope ≤ 1:2850
Jamuneswari	1:3600	Rd = 2.41	100 to 650 =375	D_d =0.18 (∑L=245 km Area=1373 km²)	Does not match (max. 2100m deviation, no breaking of stream line exists)	Slope ≥ 1:3600
Chitra	1: 13000	Rd = 4.00	150 to 350 = 259	D_d =0.12 (∑L=139 km Area=1187 km²)	Does not match (max. 5000m deviation, no breaking of stream line exists)	Slope ≥ 1:3600
Sib_river	1: 5000	Rd = 3.85	600 to 1200=900	D_d =1.94 (∑L=89.25 Area=46.05 km²)	Does not match (max. 1000m deviation, no breaking of stream line exists)	Slope ≥ 1:3600
Garai-Madhumati-Kaliganga	1:32000	Rd = 2.00	250 to 650 = 450	D_d =0.05 (∑L=95 km Area=1930 km²)	Does not match (max. 2300m deviation and breaking of stream line exists)	Slope ≥ 1:3600
Kushiara	1:13000	Rd = 4.5	150 to 300 =225	D_d =0.13 (∑L=139 km Area=1038 km²)	Does not match (max. 550m deviation and breaking of stream line exists)	Slope ≥ 1:3600
Banar River	1:7000	Rd = 3.25	300 to 1000=650	D_d =0.14 (∑L=106 km Area=772 km²)	Does not match (max. 2600m deviation and no breaking of stream line exists)	Slope ≥ 1:3600
Tulshi-Ganga	1:9000	Rd = 5.5	400 to 1000=700	D_d =0.15 (∑L=240 Area=1550 km²)	Does not match (max. 2500m deviation and breaking of stream line exists)	Slope ≥ 1:3600

- Measurement has been taken from pixel value of the processed SRTM DEM

The drainage density (Dd) is the ratio of the total length of streams to the total area of the watershed. The drainage density performs a rapid storm response. The value typically ranges from 0.94 to 3.5 km/km^2 (MSU, 2008). The bifurcation ratio (Rb) is defined as the ratio of the number of streams of any order to the number of streams of the next highest order (Horton, 1945).

Values of Rb typically range from the theoretical minimum of 2 to around 6 and typically, the values range from 3 to 5 (MSU, 2008). Normally, the main stream is delineated, and the slope (S) is computed as the difference in elevation (ΔE) between the end points of the longest flow path divided by the hydrologic length of the flow path (L).

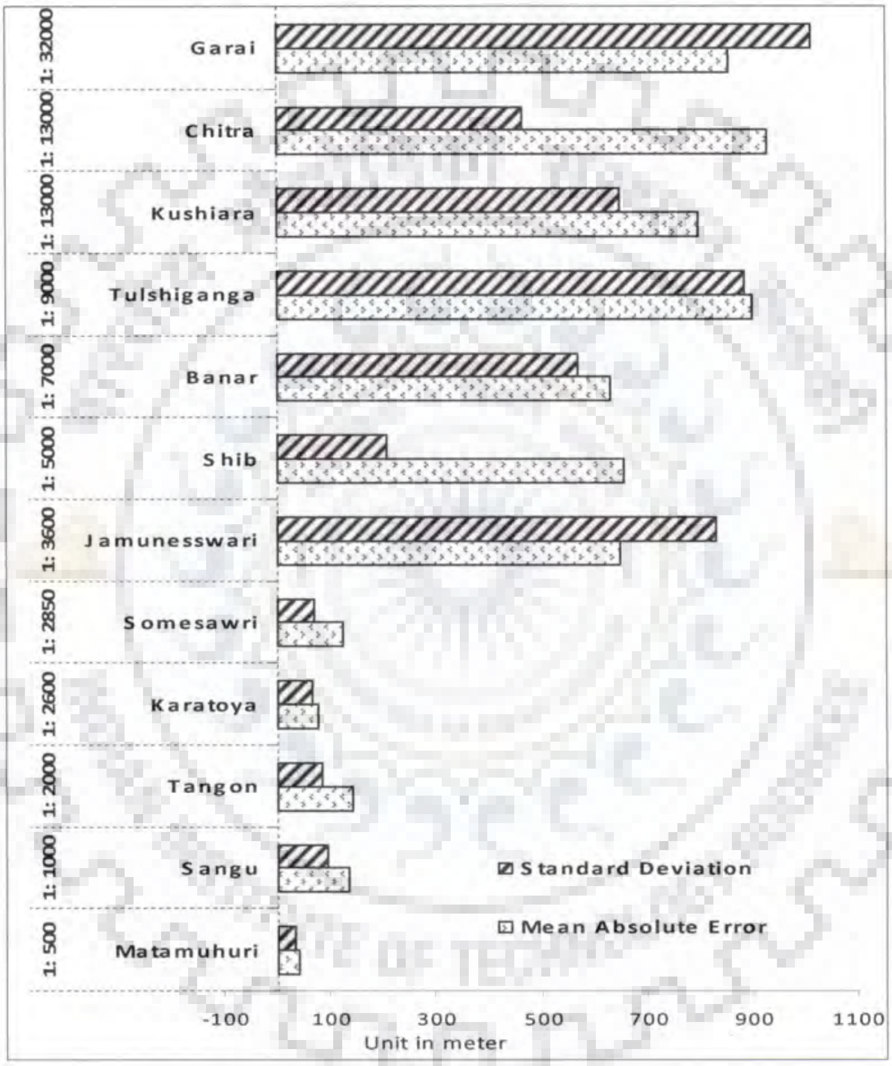


Figure 3.4: Comparison of mean absolute error with the catchment slope. The figure clearly shows that the error is increasing significantly with the increase in slope.

The values of the geomorphological parameters have been calculated using inputs from delineated drainage network. Table 3.1 shows a comparison of the geomorphological parameters with the deviation of the catchment. The comparison shows that among the catchment parameters like slopes, bifurcation ratio, and drainage density, only slope is the main governing parameter. All other catchment characteristics other than the slope have no effect on river network delineation. The delineated catchments of slope 1:3600 or more flat shows enormous error in stream delineation. Large deviations in delineated river network have been found when compared with the digital river network of BWDB and with Google Earth's Images. The catchments having slope 1:2850 and more steep have been delineated correctly. However, a conclusion could not be established between slopes 1:2850 and 1:3600. The calculated MAE of all the catchments shows that it increases with respect to decrease of slope as seen in Figure 3.4.

3.5 Conclusions

A study has been undertaken to evaluate the performance of 90 m SRTM DEM in delineation of drainage network using Hydrology tool of ARCGIS, for the flat terrain of Bangladesh. Twelve catchments have been selected from the five hydrological zones of Bangladesh. It is concluded that, in flat terrains, having a slope flatter then 1:2850, delineation of drainage network must be carried out carefully using the Hydrology tool of ArcGIS software that uses the D8 method for delineation of drainage pattern and catchments. It is also recommended that other techniques excluding D8 method as implemented in ArcGIS, should be experimented with before a general conclusion about the use of SRTM data in flat terrains could be drawn.

Chapter 4 - Evaluation of ECMWF and TRMM Rainfall Data for Flood Studies

4.0 Introduction

Rainfall estimates are required for developing flood forecasting and early warning systems. The estimated rainfall products from satellite data and numerical weather prediction modelling systems are particularly useful for trans-boundary basins like Ganges, Brahmaputra and Meghna (GBM basins), where observed data exchange does not happen in real time (MoWR, 2008).

The rainfall stations in Bangladesh are sparsely located rendering the estimation of floods difficult. The rainfall is highly variable in space and time. For example, at Sylhet in the northeastern part of Bangladesh, the annual average rainfall is 4180 mm; at Sunamganj near the foot of the abrupt Meghalaya Plateau it is 5330 mm; and rainfall of 6400 mm is recorded at Lalakhal. Moreover, Cherapunji (India) records an astonishing average of 10820 mm annually and is only 16 km away from the Bangladesh northern border (Asiatic Society of Bangladesh, 2006 and, ODA and JICA, 1993).

The Bangladesh Meteorological Department maintains 34 hydrometeorological observatories in the country where observation, recording and archiving of rainfall data are done. Among these 34 stations, only two stations i.e. Sylhet and Srimangal observe rainfall in the northeastern zone which lies in the Meghna basin; similarly in the northwestern part of Bangladesh partially in the Ganges and partially in the Brahmaputra basins which are prone to chronic floods have a few stations only.

Under this study, as indicated in Chapter 2, ECMWF and TRMM daily rainfall data for three locations of Ganges, Brahmaputra and Meghna (GBM) basins in Bangladesh have been analyzed by visual verification, yes/no-dichotomous verification, and continuous variables verification methods. Bangladesh Meteorological Department (BMD) rainfall data are used as the reference data. These locations are Dinajpur in the Ganges basin, Rangpur in the Brahmaputra basin, and Sylhet in the Meghna basin. The location of these three stations are shown in Figure 4.1.

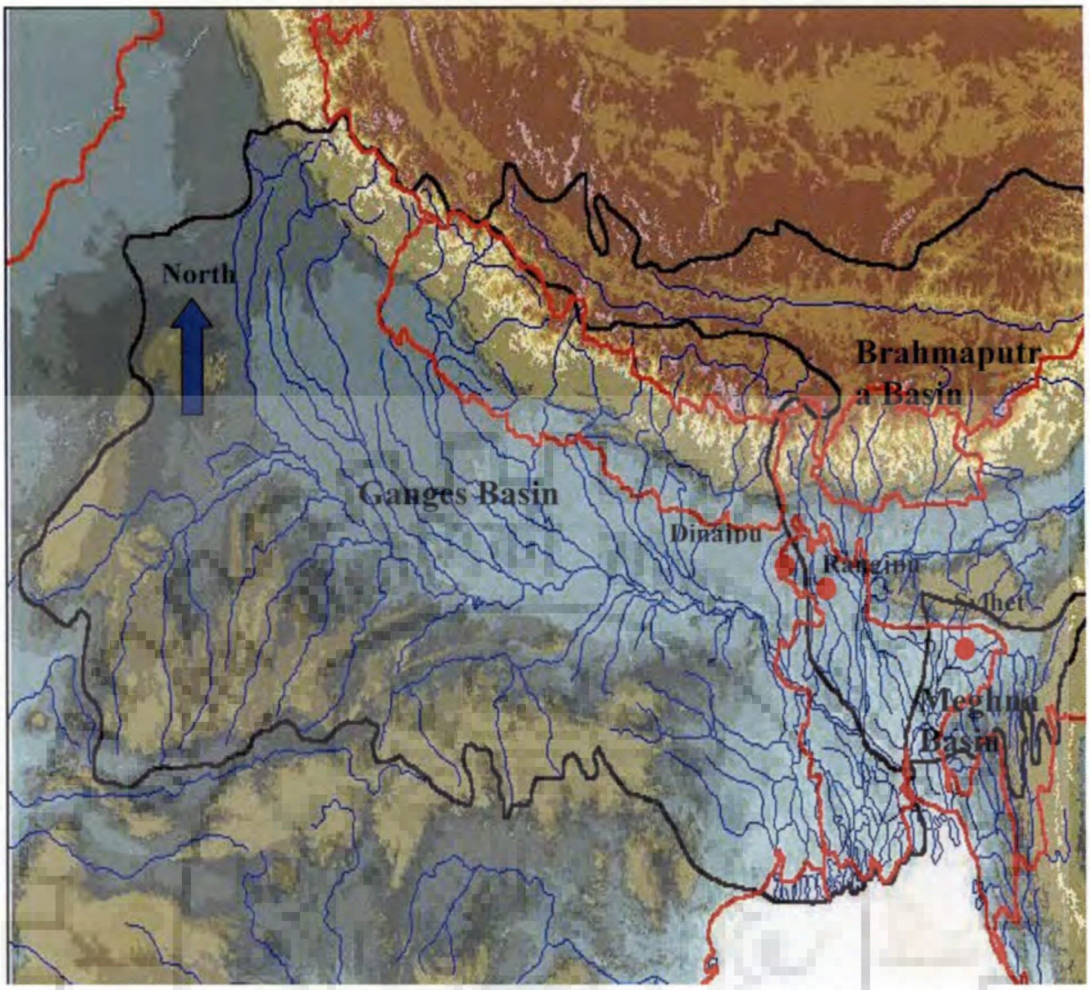


Figure 4.1: The map shows the GBM basin. The location of the three rainfall stations selected in GBM basins lying in Bangladesh are also shown with red color.

Chowdhury and Ward (2004) described the GBM basins and their hydrometerological variabilties. Mirza et al. (1998) mentioned that the Ganges and Brahmaputra rivers originate on the southern and northern slopes of the Himalayas respectively, and traverse thousands of kilometers debouching into the Bay of Bengal. Mirza et al. (1998) analyzed trends and persistence in time series of annual precipitation for each of the 16 meteorological subdivisions covering the GBM basins. He found that precipitation in the Ganges basin is by-and-large stable whereas the rainfall of Brahmaputra and Meghna basins in Assam (India) show persistence.

The Meghna River is smaller and originates in the southern slopes of the mountain range in the north of Manipur, India. These three river basins cover about 1.75 x 106 km^2 across five different countries: China, Nepal, India, Bhutan and Bangladesh. Chowdhury and Ward (2004) correlated the stream flows of these rivers in Bangladesh with the rainfall in the upper catchments and found that the stream flows in Bangladesh could be estimated for 1 to 3 months in advance (especially for the Ganges and Brahmaputra rivers). Chowdhury and Ward (2004) emphasized the need of developing a spatially distributed knowledge base for seasonal stream flow forecast in the GBM basins in Bangladesh. Satellite data are a valuable source to derive the information on clouds and rainfall (Todd et al., 1995). The objective of this study is to determine the rainfall statistics of TRMM and ECMWF RF data for evaluation of its potentiality in flood studies like design flood estimation, calibration and validation of hydrologic models, and forecasting of flood etc.

4.1 Data used for the study

ECMWF rainfall data

ECMWF is the leading global modelling center, producing very high resolution analyses, and forecasts at various time scales. In last few decades, ECMWF has maintained high standards for its products (Woods, 2006). ECMWF's analysis and re-analysis products are very popular worldwide for various applications including flood and hydrological processes. Improvements in representation of the moist physics processes in the ECMWF model have showed better diurnal cycle of convective rainfall in tropics (Tompkins, et al., 2004; Bechtold, et al., 2004; Thepaut, et al., 2005).

In a typical 12-hour period, there are 75 million pieces of available data assimilated to the model, out of which around 98% are from satellites. The ECMWF rainfall data used in this study comes from the data assimilation system of the ECMWF medium-range analysis-forecast system. The high resolution global model uses the six-hours forecast as the first guess in the analysis. During six-hourly data assimilation cycle (four times a day) fresh atmospheric observations are added to this first guess to produce the final analysis. These six-hour model rainfall forecasts (first guess in analysis) are supposed to be very accurate and close to observations. From the six-hourly analysis data files of ECMWF, six-hourly rainfall values are accumulated to make a daily (past 24 hours) rainfall value for each grid of the region of study. This daily rainfall data from ECMWF model's assimilation cycle is at 0.5^{o} x 0.5^{o} resolutions.

The ECMWF rainfall data have been collected from the project 'Climate Forecasting Applications Network' (CFAN), being implemented by Bangladesh Water Development Board (BWDB), the sole agency responsible for developing and managing water resources in Bangladesh. The ECMWF rainfall data are also available on the CFAN website. The CFAN data are based on satellite data from NOAA National Center for Environmental Protection (NOAA/NCEP) and output of the ECMWF model. The monsoon intra-seasonal oscillations (MISO) statistical prediction scheme has been used in experimental operational mode in the CFAN project (Webster and Hoyos, 2004). ECMWF analysis and forecasted rainfall are also used for flood related applications in Bangladesh. The ECMWF rainfall data of two years i.e. 2004 and 2006 covering the tropics between 70^{o}E, 20^o N and 100^{o}E, 35^{o}N with grid cells of resolution 0.5^0 by 0.5^0 was collected and used in this study.

ECMWF global model has a state-of-art data assimilation system and representation of physical process. One basic assumption in data assimilation cycle is that the first guess (6-hr forecast) from the model is very close to observations. It is well known that the RMSE of the analysis (output from data assimilation cycle) is always the least compared to the short or medium range forecasts for the model (Andersson and Thepaut, 2008). The model does not have major issues related to spin-up of the hydrology related fields like total precipitation rate, precipitation minus evaporation and total column water vapor (Uppala et al., 2008). Therefore, the analysis product from the data assimilation system is used here as proxy rainfall observations in our flood application research study. As the TRMM satellite life period is over, conclusions from the use of such proxy data from weather modeling systems will provide useful guidelines for flood management and planning studies like this.

TRMM Rainfall Data

Over the last three decades, researchers have been using satellite information to estimate rainfall. The satellite and gauge data were combined by Huffman et al. (1997) to create a post-real-time monthly satellite–gauge (SG) combination, which is a Tropical Rainfall Measuring Mission (TRMM) research-grade product (3B43). An algorithm to merge TRMM Multi-satellite Precipitation Analysis (TMPA) satellite estimates with the Indian Meteorological Department's rain gauge values were tested for the Indian region (Mitra et al., 2009). Mitra et. al (2009) found that the merged data is more informative than the TMPA values alone. Huffman et al. (1997) and Adler et al. (2003) described the computation of monthly TMPA rainfall at a relatively coarse scale, 2.5°× 2.5° latitude–longitude grid, by combination of satellite and gauge information within reasonable error characteristics under Global Precipitation Climatology Project (GPCP). Huffman et al. (2007) also described that the TMPA dataset continues the trend toward routine computation and distribution of finerscale precipitation estimates. The dataset covers the latitude band 50°N–S for the period from 1998 to the present.

The TRMM rainfall data have been downloaded from the NASA TRMM website. The Tropical Rainfall Measuring Mission of the National Aeronautics and Space Administration (NASA) produces merged three-hourly rainfall rates incorporating space borne radar, microwave data and infrared imagery. The data are then processed at USGS (United States Geological Survey) EROS (Earth Resources Observation and Science) centre to convert them to daily accumulations and for reforming to GIS-ready images.

The NASA-TRMM product (version 3B42) covers the tropics between 50^o north and 50^o south with grid cells of spatial resolution 0.25^o by 0.25^o. The NASA TRMM daily rainfall products are available from 1998 to the present. The processed rainfall data are made available within 12 hours after the remote sensing data collection. While other satellite-derived rainfall products are available, the NASA TRMM 3B42 products are used in this application because of their superior performance in regions with limited in-situ gauges (Dinku et al., 2007). The TRMM 3B42 satellite estimate is a merged product comprising calibrated IR rainfall and microwave-rainfall. These satellite estimates are again calibrated by precipitation radar of TRMM and gauges over land. The final product of TRMM 3B42 is a gridded data available 3-hourly for extended tropical regions of the globe. Even though, TRMM is a polar-orbiting satellite, the merging of IR and microwave-rain from many other satellites compensate for the deficiency to produce rainfall data of very high quality (Huffman et al., 2007).

Ground Observation Data

The observed rainfall data were available from two sources i.e. Bangladesh Meteorological Department (BMD) and Bangladesh Water Development Board (BWDB). The daily rainfall data of Rangpur, Dinajpur and Sylhet stations were collected for the years 2004 and 2006 from either source and used in this study. These two years are selected on the basis of full data from all source, i.e. model, satellite and gauges were available.

Floods are generally associated with either relatively severe weather systems passing over Bangladesh or persistence of very active monsoon conditions. In early June of 2004, heavy monsoon rains occurred in the Meghna basin, which reached the ever-highest recorded flood level in early-July. The Ganges and Brahmaputra rivers also swelled their banks in early-July, due to heavy rains in the north of the country. Eventually, thirty-eight percent area and thirty six million people (about twenty-five percent of the population) were affected, sustaining heavy property damage and loss of lives. During 2006 monsoon season, as many as 16 low-pressure systems formed over the Indian region (12 over the Bay of Bengal, one over the Arabian Sea, and three over land). Of these systems, eight intensified (seven over the Bay of Bengal and one over land) into monsoon depressions and one into a severe cyclonic storm (over the Arabian Sea). During the study period of these two years, there were enough transient weather systems associated with the changing synoptic atmospheric conditions to represent typical monsoon associated flood events. Therefore, as a showcase, results from these two years will indicate the reliability and usability of rainfall estimates from satellites and NWP.

4.2 Methodology of evaluation

In this study ECMWF and TRMM rainfall data for the years 2004 and 2006 are compared and analyzed with the ground observation daily rainfall data at Dinajpur (88.68°E, 25.65°N), Rangpur (89.73°E, 25.73°N) and Sylhet (91.88°E, 23.30°N) climate stations in the Ganges, Brahmaputra, and Meghna (GBM) basins in Bangladesh respectively (Figure 4.1). The selection of stations and data collection years is on the basis of availability of data from Bangladesh Water Development Board (BWDB), Bangladesh Meteorological Department (BMD), and availability of data from CFAN website and TRMM RF data portal.

Murphy (1993) described three types of "goodness" in verification of consistency, quality and value. Murphy (1993) also described nine attributes that contribute to the quality of estimation viz. bias, association, accuracy, skill, reliability, resolution, sharpness, discrimination, and uncertainty. Stanski et al. (1989) classified the verification methods in visual, dichotomous and continuous variable verification categories. These categories are used for the validation of quantitative rainfall estimates in this study.

4.2.1 Visual verification

Visual verification methods are based on looking at the computed and observed value side-by-side using instantaneous human judgment to differentiate the estimation errors. Common way to present data for verification of how the values of the estimation differ from the values of the observations. The verification of continuous estimations often includes some exploratory plots such as time series graphs (Nurmi, 2003), histogram (Hirsch et al., 1993), and Cumulative Distribution Function (CDF) curves (Hirsch et al., 1993).

4.2.2 Yes/no-dichotomous verification

The yes/no-dichotomous verification methodology is fundamentally based on the statistical framework for the verification developed by Murphy and Winkler (1987) which was later modified for aviation forecasts by Brown et al. (1997). The dichotomous method describes, "yes, an event will happen", or "no, the event will not happen". Precipitation estimation has yes/no response. In this case, threshold may be specified to separate "yes" and "no", for example, rainfall greater than 5 mm. A contingency table is given by (Brown et al., 1997) for the frequency of "yes" and "no" estimates and occurrences are presented in Table 4.1. The four combinations of estimations (yes or no) and observations (yes or no), called the *joint distribution*, are:

- *Hit* - event estimation to occur, and did occur
- *Miss* - event estimation not to occur, but did occur
- *False Alarm* - event estimation to occur, but did not occur
- *Correct Negative* - event estimation not to occur, and did not occur

Table 4.1: Contingency table for yes/ no dichotomous method

Contingency Table				
		Observed		
		Yes	no	Total
Estimate/ Forecast	yes	*Hits*	*False Alarms*	*Estimate/ Forecast yes*
	no	*Misses*	*Correct Negatives*	*Estimate/ Forecast No*
Total		*Observed yes*	*Observed No*	*Total*

A perfect estimation system would produce only *hits* and *correct negatives*, and no *misses* or *false alarms*. Different *categorical statistics* are computed from the contingency table to verify the estimation performance. Categorical statistics that can be computed from the yes/no contingency table are described by WMO/TD-No.1485 (2008) and also given in Appendix 4.1.

4.2.3 Continuous variables verification

Finally, verification of continuous variables measure how the *values* of the estimations differ from the values of the observations. Verification of continuous estimations often include various summary scores as described by Lettenmaier and Wood (1993) and WMO/TD-No. 1485 (2008) and also given in Appendix 4.2 .

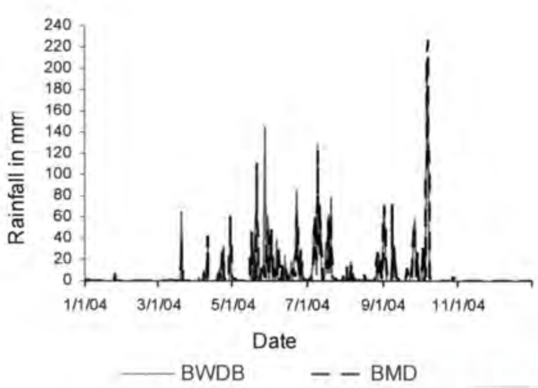
4.3 Data analysis and result discussion

The different verification methods have been applied for the sensitive analysis of the estimated data at Rangpur, Dinajpur and Sylhet during the year 2004 and 2006. The analysis and results have been discussed below.

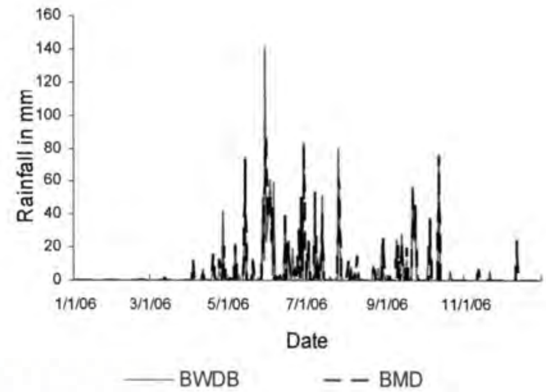
4.3.1 Analysis of observed rainfall data

The reliability of the BMD RF data have also been verified with the third party RF data of BWDB. In this regard, verification methods for visual and continuous variables have been applied to both the daily and monthly data. The Rainfall (RF) data collected by BMD have been considered as the reference observed data in this study.

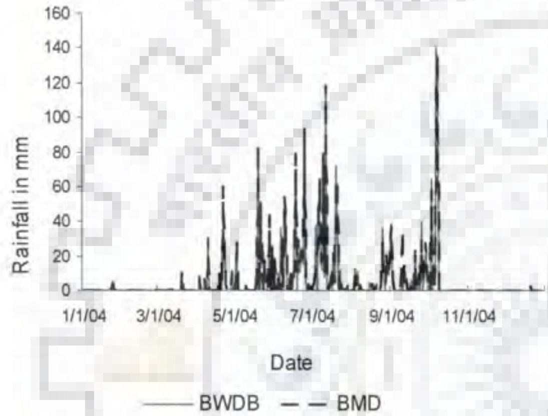
For visual verification, time series plot of daily rainfall data are shown in Figure 4.2. In Figure 4.2, it is found that the data are matching with some exception like higher values in BWDB data during extreme events. Time series of monthly rainfall data are plotted in Figure 4.3. Figure 4.3 illustrates that the Rangpur station shows more values in May 2004. The analyses of Figures 4.2 and 4.3 depicts that most of the differences between BWDB and BMD data are found in May, June and July. The differences in the data occurred systematically and are found smaller in 2006 than in 2004. This indicates that there are different observational techniques either BWDB or BMD stations. BWDB observes the rainfall data manually whereas BMD measures by automatic raingauge. Data at Dinajpur in 2004 and 2006, Sylhet 2004 and 2006, and Rangpur in 2006 contain consistent bias: monthly total of BMD are greater than BWDB. Inconsistency of data at Rangpur in 2004 (BMD<BWDB) also implies some typical reasons, like change of data reader or instruments.



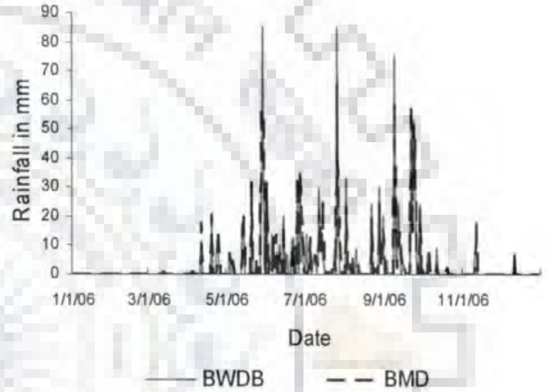
Rangpur 2004



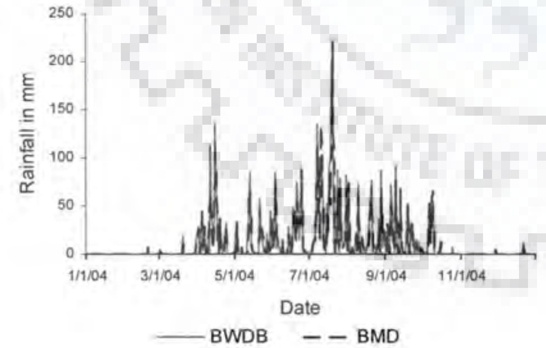
Rangpur 2006



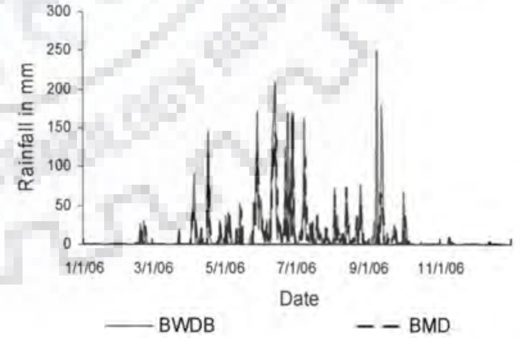
Dinajpur 2004



Dinajpur 2006

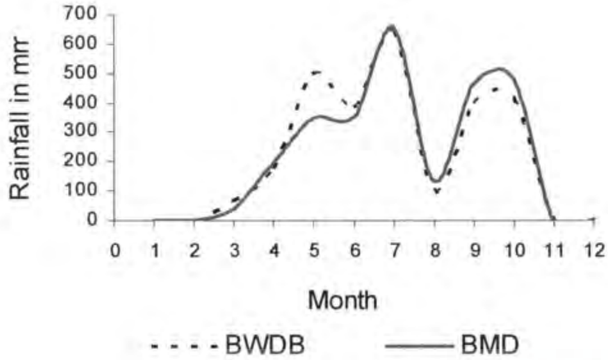


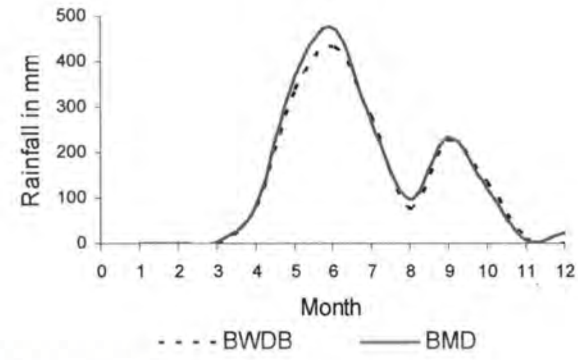
Sylhet 2004



Sylhet 2006

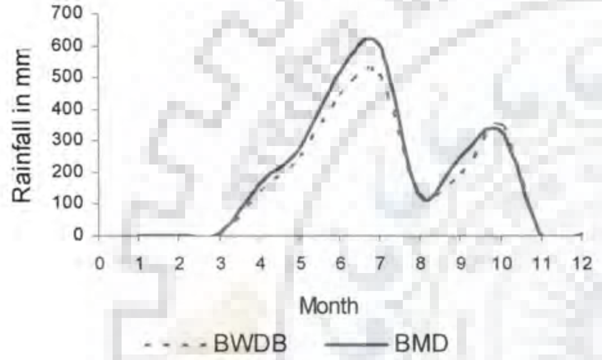
Figure 4.2: Time series of daily rainfall data observed by BWDB and BMD.

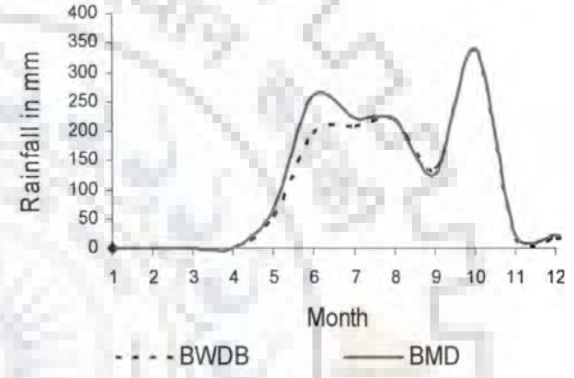




Rangpur 2004

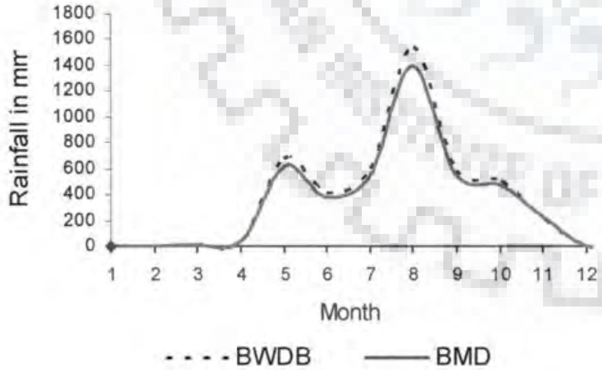
Rangpur 2006

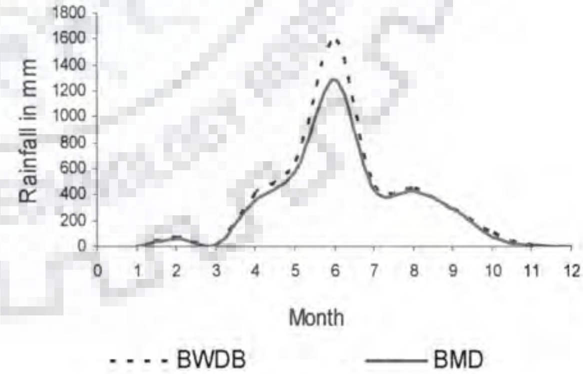




Dinajpur 2004

Dinajpur 2006





Sylhet 2004

Figure 4.3: Time series of monthly rainfall data observed by BWDB and BMD.

For verification by continuous variables additive bias i.e. mean error (ME), multiplicative bias (Bias), coefficient of correlation (r), and skill score (SS) are calculated. For calculation of skill score (SS), BMD data has been taken as the reference data. Table 4.2 gives the comparison of the biases. The comparison shows reasonably good agreement between BMD and BWDB rainfall data. The ME, Bias, r, and SS of daily rainfall at Rangpur (Brahmaputra basin) and Dinajpur (Ganges Basin) show better agreement between BMD and BWDB but other stations have some disagreement. The Sylhet station (Meghna Basin) is showing the more disagreement between two set of data which might have been caused from geographical location of stations and measurement techniques. CDF of rainfall in each year for three stations in both the years are plotted and shown in Figure 4.4. The comparison of the probabilities again show good agreement between BMD and BWDB data.

Table 4.2: Statistical comparison of BMD and BWDB observed rainfall data

Station	Year	Data Type	Continuous variable statistics			
			ME	Bias	r	SS
Rangpur	2004	Daily	0.01	1.00	0.88	0.75
		Monthly	-0.02	1.00	0.97	0.97
	2006	Daily	0.00	1.00	0.86	0.73
		Monthly	0.29	0.94	0.99	0.99
Dinajpur	2004	Daily	-0.72	1.13	0.99	0.98
		Monthly	0.73	0.89	0.99	0.98
	2006	Daily	-0.27	1.08	0.89	0.79
		Monthly	0.27	0.92	0.99	0.98
Sylhet	2004	Daily	0.92	0.93	0.92	0.84
		Monthly	0.94	1.08	0.99	0.99
	2006	Daily	1.35	0.88	0.82	0.67
		Monthly	1.56	1.28	0.97	0.88
Reliability Assessment			ME is minmum error for Rangpur and Dinajpur but Sylhet shows some non-reliability.	Minimum bias for Rangpur and Dinajpur but Sylhet shows small non-reliability	Very good correlation	Very Good for Rangpur and Dinajpur but Sylhet shows some non-reliability in 2006

Having seen a good agreement between BMD and BWDB observed rainfall data and considering the fact that BMD is the main agency for collecting meteorological data in Bangladesh, the BMD rainfall data have been used as the reference data for further analysis of ECMWF and TRRM data.

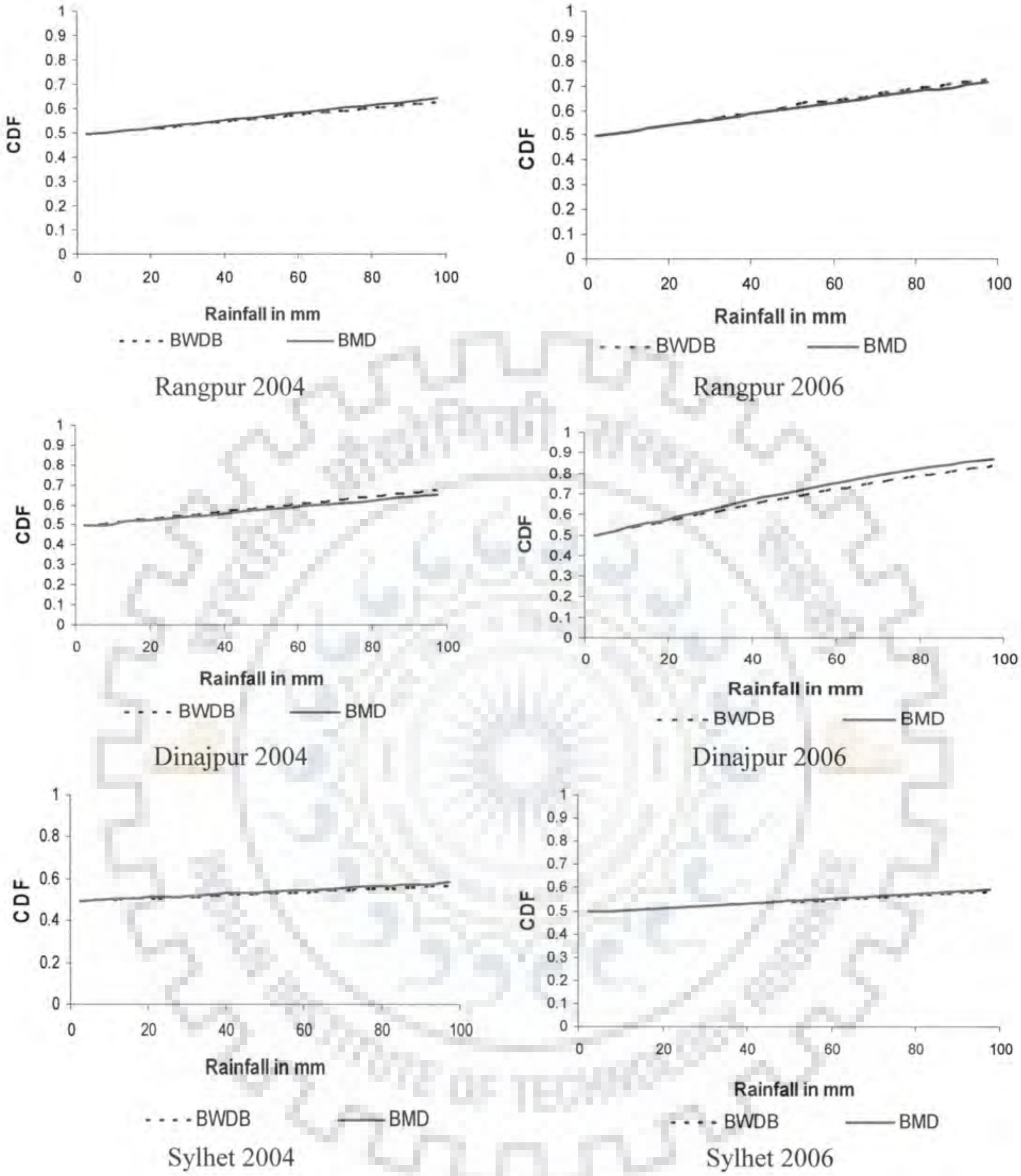


Figure 4.4: Comparison of CDF of observed rainfall of BWDB and BMD.

4.3.2 ECMWF and TRMM data preparation

The daily time series ECMWF and NASA-TRMM 3B42 RF data has been extracted from its spatial distribution grid boxes for the stations at Rangpur, Dinajpur, and Sylhet during the year 2004 and 2006.

The time series of ECMWF data for four corners of the grid boxes under the domain of each of the locations have been extracted using a visual basic programme. Then the time series of the three locations at Long 89.23°E, Lat 25.73°N and Long 88.68°E, Lat 25.65°N have then been derived by arithmetical mean method (Chow, 1988), inverse distance-weighing (IDW) method (Smith,1993) and area-averaged method (Chow, 1988). The derived time series have been compared with the observed data of BMD. The correlation coefficient between derived time series of ECMWF RF data and BMD observed rainfall at three location Rangpur, Dinajpur, and Sylhet are given in the Table 4.3. It has been found that the IDW is giving better result.

Smith (1993) described the Inverse Distance-Squared Method, it is commonly used for this purpose and the Rainfall Estimation for the j-th grid box is

$$\overline{P_j} = a \sum^{n} d_{ij}^{-2} P_i \qquad (4.1)$$

Where d_{ij} is the distance from gauge i to centre of grid box j and a is inverse of the sum of the Inverse Distance-Squared values for all gauges:

$$a = \left(\sum_{i=1}^{n} d_{ij}^{-2} \right)^{-1} \qquad (4.2)$$

Hence, the data set derived using IDW interpolation method have been used for further analysis in this study.

Table 4.3: Comparison of the extracted time series of ECMWF RF data by different methods with the BMD observation

Station	Year	Arithmetical Mean	Area Averaged	Inverse Distance Weighing
Rangpur	2004	0.55	0.55	0.56
	2006	0.59	0.58	0.59
Dinajpur	2004	0.51	0.52	0.52
	2006	0.49	0.48	0.5
Sylhet	2004	0.41	0.42	0.44
	2006	0.43	0.44	0.45
Selection of Method		After comparing all methods, it is decided that the Inverse Distance Squared method is acceptable.		

The TRMM Rainfall data have been derived for the three stations at Rangpur, Dinajpur and Sylhet from the spatial distributed grid directly from the their website and used in this study without any preprocessing

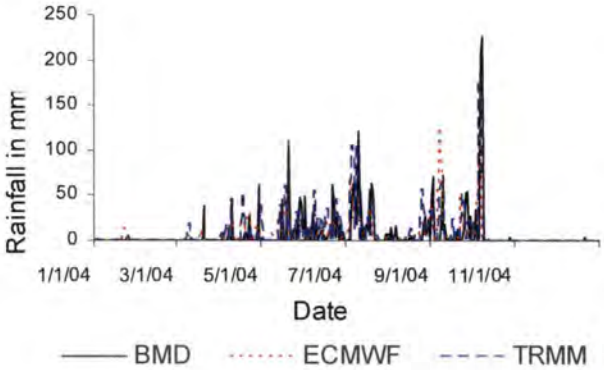
4.3.3 Evaluation of ECMWF and TRMM rainfall data

The methods of visual verification, yes/no dichotomous statistics and continuous variables verification have been used in this study and the results are discussed in this section. In visual verification methods, bar charts of monthly values of time series, histograms of relative frequency of rainfall, plotting cumulative distribution function (CDF) have been used to compare the ECMWF and TRMM data with BMD data.

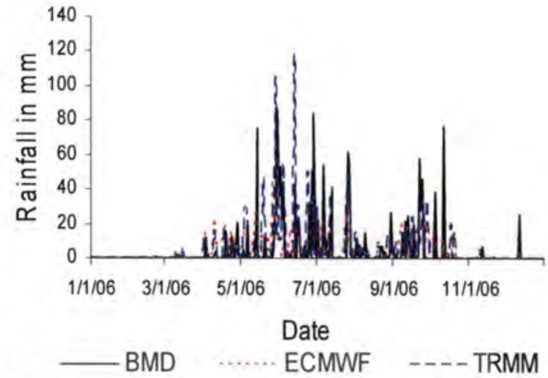
Figure 4.5 shows the daily rainfall time series comparison where the pattern of ECMWF and TRMM RF data are matching with the observed rainfall in general. Some deviations are observed close to high and low rainfall values in either case. Peaks of TRMM RF data are found close to the observed rainfall but low rainfall values are not matching with the observed rainfall. ECMWF RF data matches the high rainfall values better than TRMM data however shows higher values for low rainfall data.

Figure 4.6 shows the bar chart of monthly ECMWF, TRMM and BMD observed RF data. It shows that the monthly values of ECMWF and TRMM RF data are close to the monthly values of BMD observed RF data with few random differences in the case of extreme events of higher or lower rainfalls such as in June: there is 100 mm difference between ECMWF and TRMM rainfall data at Dinajpur in 2004.

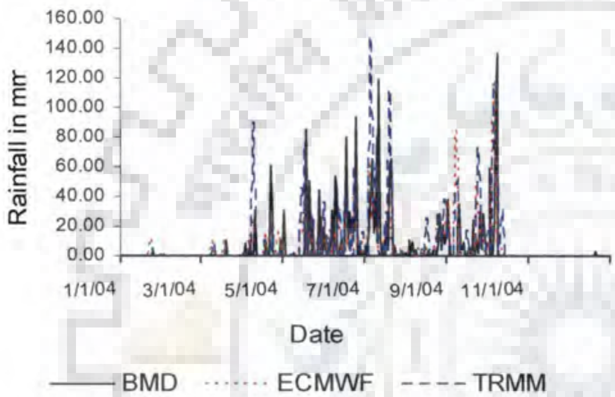
At Sylhet in Meghna basin, during monsoon both ECMWF and TRMM rainfall data show significantly lower value than the observed value. Comparison between ECWMF and TRMM shows that in most cases the monthly rainfall totals are in agreement with each other.



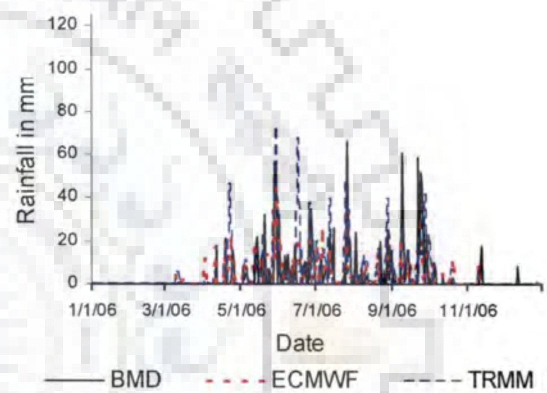
Rangpur 2004



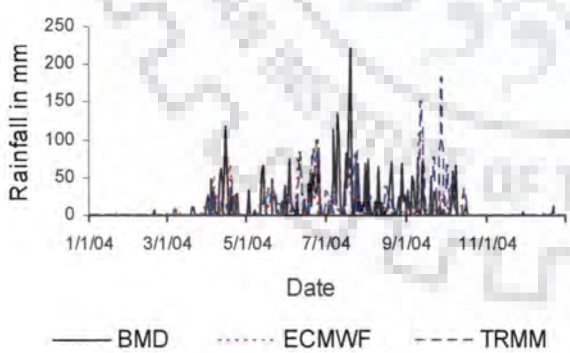
Rangpur 2006



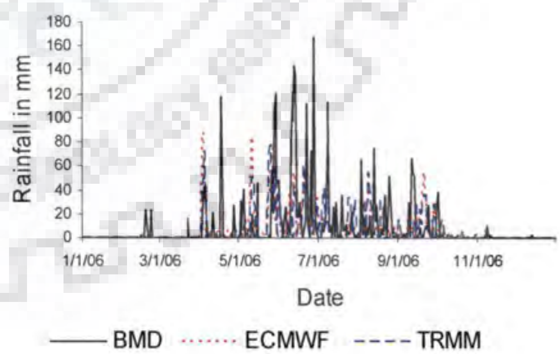
Dinajpur 2004



Dinajpur 2006



Shylhet



Shylhet

Figure 4.5: Time Series Plots of BMD observed (black line), ECMWF (red dotted), and TRMM (blue dash) daily rainfall data

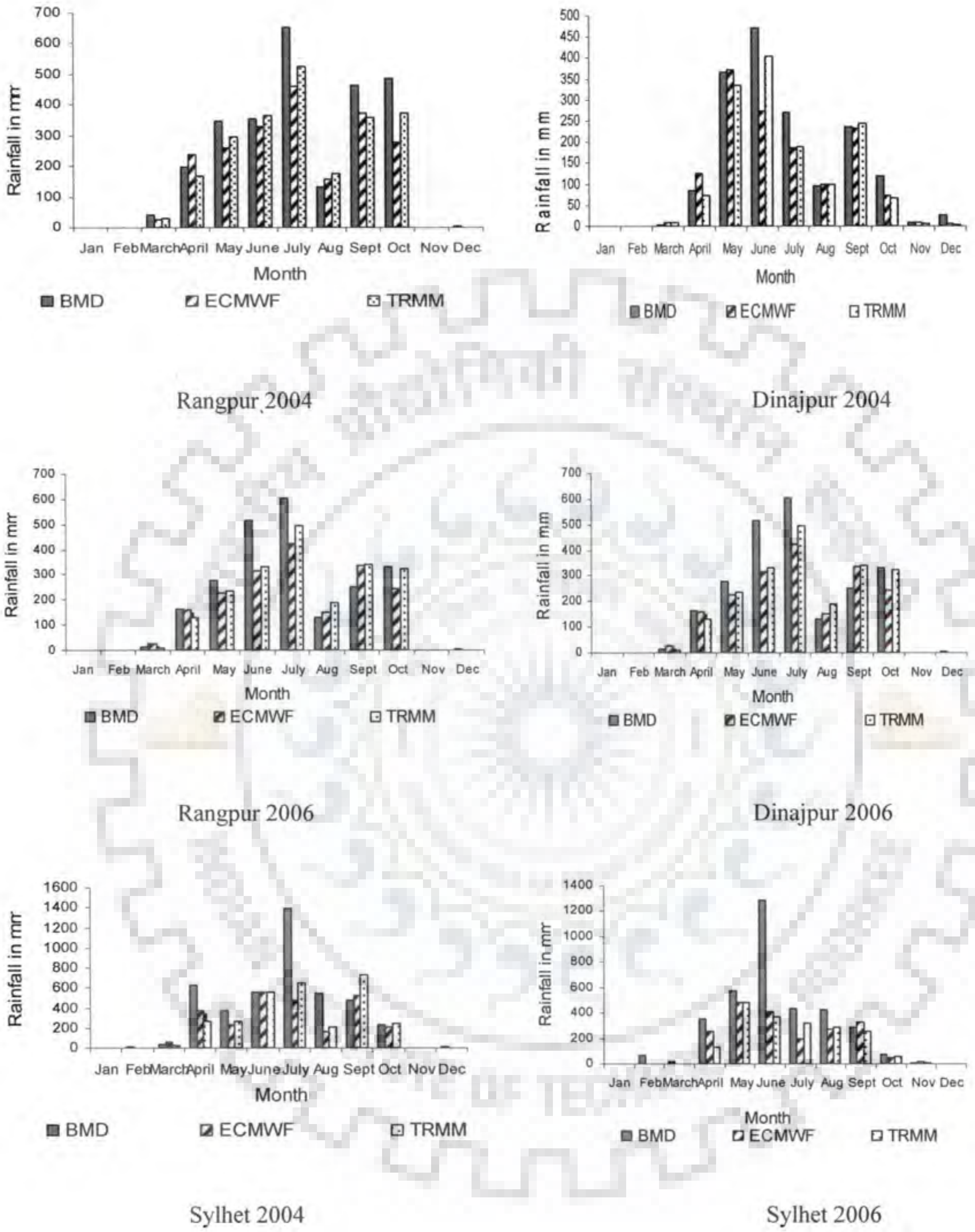


Figure 4.6: Bar chart of BMD observed, ECMWF, and TRMM monthly rainfall data

The comparison of the relative frequency histograms of ECMWF, TRMM, and BMD daily rainfall data are shown in Figure 4.7. The figure shows that the different data classes have good agreement among ECMWF, TRMM, and BMD RF data.

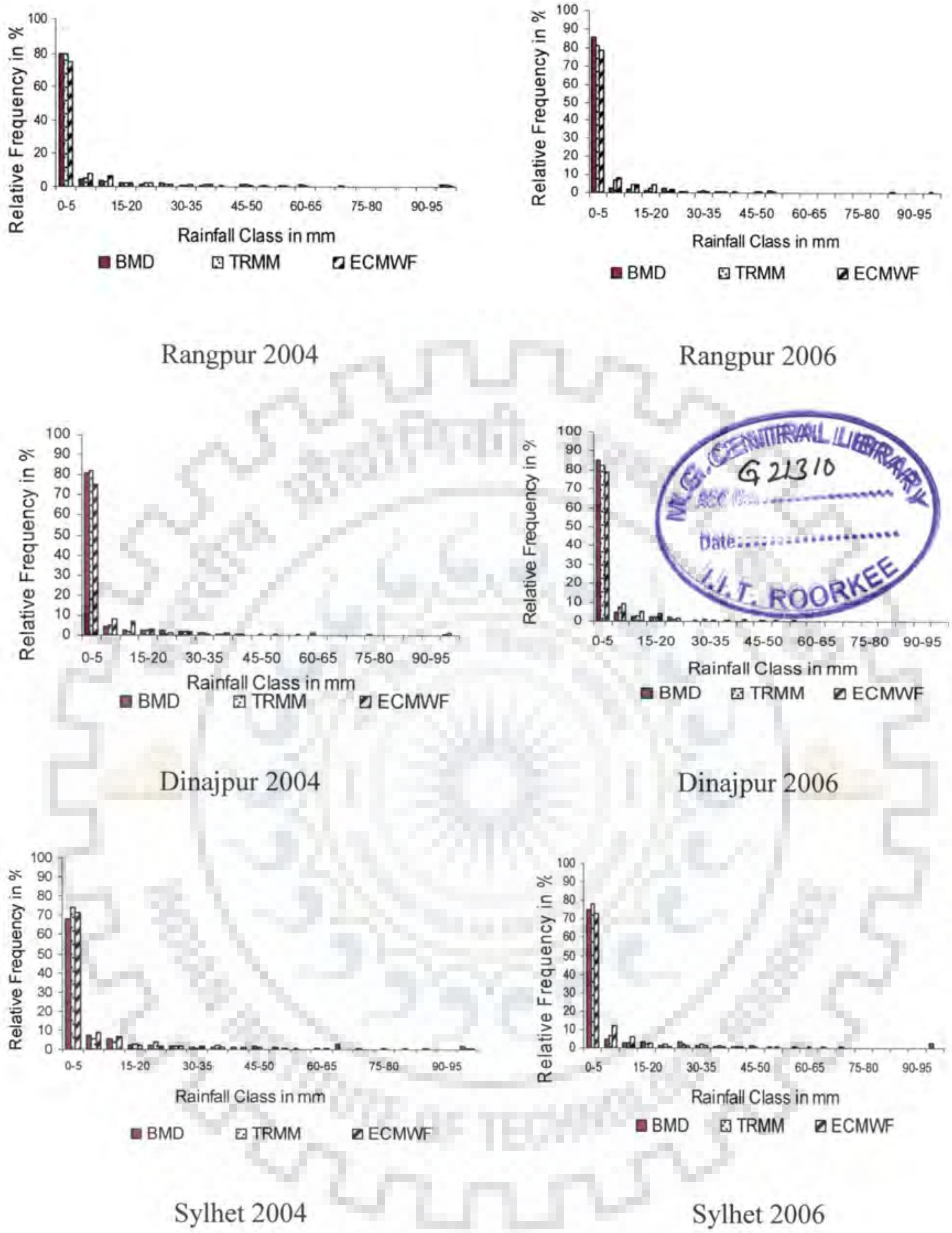


Figure 4.7: Histogram of relative frequency of rainfall distribution of BMD observed, TRMM and ECMWF daily RF data

Figure 4.8 shows the inter comparison of CDF of ECMWF, TRMM, and BMD RF data. From Figure 4.8, it is observed that CDF of ECMWF rainfall data are passing above the CDF of BMD observed rainfall data for all the stations. CDF of TRMM rainfall data are passing close to CDF of BMD rainfall data except at Sylhet in 2006. It implies that probability of occurrence of higher values of ECMWF rainfall data are more than the probability of occurrence of BMD RF data; whereas for TRRM RF data, it is close to that of BMD RF data. So, the flood warning using ECMWF RF data will not be any chance of missing of flood event.

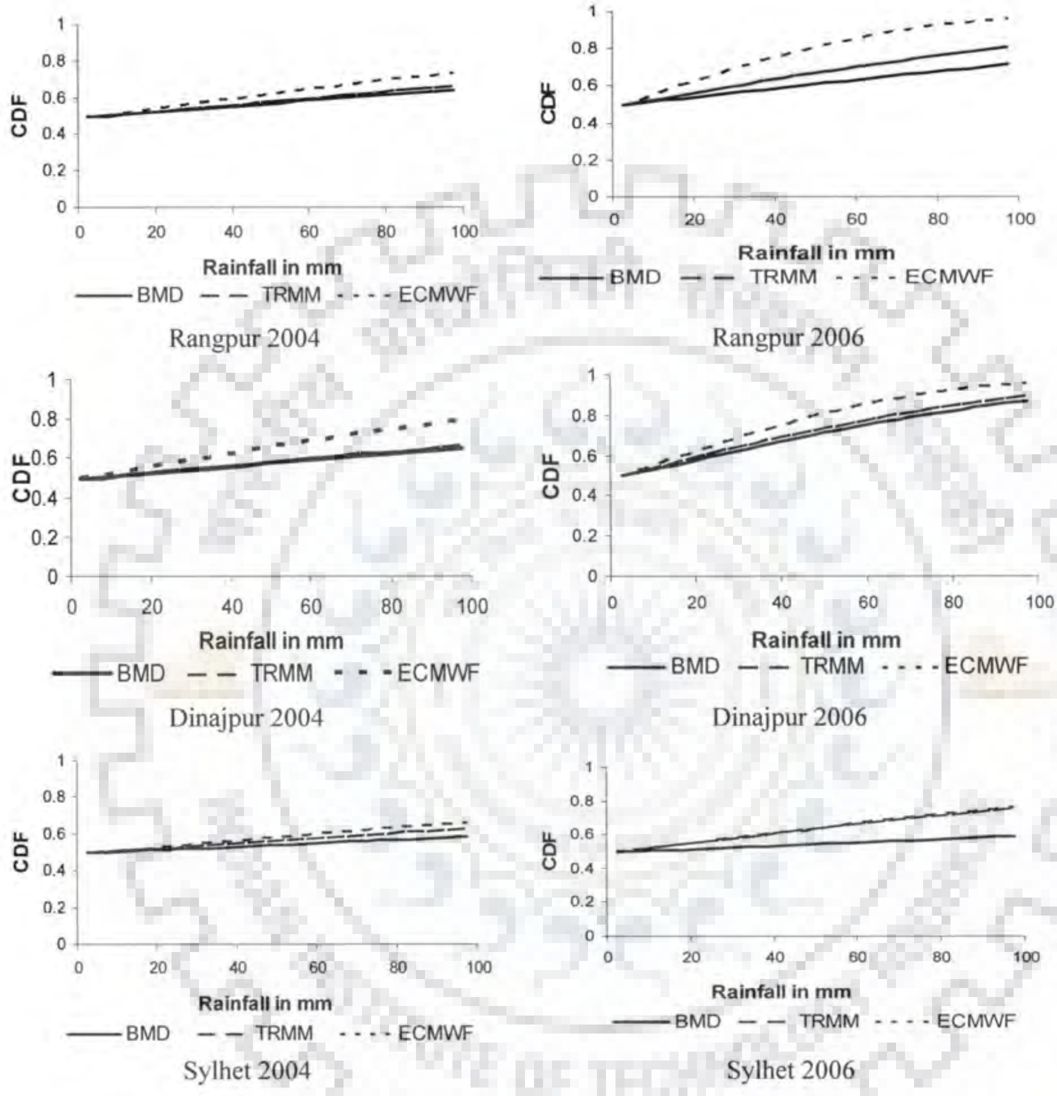


Figure 4.8: Comparison of CDF among BMD observed, ECMWF, and TRMMM daily RF data.

Table 4.4 shows the results of yes/no-dichotomous verification method. In the yes/no-dichotomous verification method, the accuracy of TRMM RF data shows the value between 0.73 and 0.76 and the ECMWF RF data gives values between 0.71 and 0.79 where perfect value is 1.00. Thus both method results in a minimum of 21% inaccuracy. This inaccuracy inflates some of the scores. The bias parameter shows that ECMWF estimates without any bias like at Sylhet in 2004 but overestimates 64% at Rangpur in 2006, whereas TRMM underestimates the rainfall data in the range of 4% to 22%.

TRMM estimates 'rain' events with a probability of detection from 0.46 to 0.61, whereas ECMWF produces 'rain' events comparatively better and probability of detection is higher (0.69 - 0.82). FAR analysis of TRMM rainfall data indicates a false alarm rate from 0.21 to 0.50. ECMWF RF data gives slightly higher false alarm rate (from 0.23 to 0.56) than the TRMM RF data. Probability of false detection analysis shows that TRMM estimates "no rain" events between 0.12 to 0.18 which is slightly better then the ECMWF RF data (0.19 to 0.30). ECMWF gives better response to detect "rain" events with a threat score between 0.37 to 0.61. The likelihood of 'yes estimation being correct' (hit) rather than 'yes estimation being wrong' (false alarm) is better for ECMWF than the TRMM data because the odds ratio (Stephenson, 2000) of ECMWF RF data is better than the TRMM RF data.

Table 4.4: Evaluation of ECMWF and TRMM daily rainfall data with BMD observed rainfall data using yes/no dichotomous verification method

Station	Year	Estimation Type	Dichotomous verification statistics						
			Accuracy	BIAS	POD	FAR	POFD	TS	OR
Rangpur	2004	TRMM	0.76	0.78	0.51	0.34	0.12	0.40	7.50
		ECMWF	0.76	1.29	0.76	0.41	0.24	0.49	9.70
	2006	TRMM	0.76	1.13	0.57	0.50	0.18	0.37	6.00
		ECMWF	0.71	1.64	0.72	0.56	0.30	0.37	6.00
Dinajpur	2004	TRMM	0.74	0.77	0.46	0.40	0.14	0.36	5.39
		ECMWF	0.76	1.24	0.74	0.40	0.23	0.49	9.58
	2006	TRMM	0.76	0.96	0.55	0.43	0.15	0.39	6.59
		ECMWF	0.71	1.45	0.69	0.53	0.29	0.39	5.48
Sylhet	2004	TRMM	0.75	0.77	0.61	0.21	0.13	0.52	10.08
		ECMWF	0.79	1.00	0.76	0.23	0.19	0.61	13.37
	2006	TRMM	0.73	0.83	0.56	0.33	0.16	0.44	6.62
		ECMWF	0.78	1.22	0.82	0.33	0.24	0.58	14.09
Evaluation of the Statistical Parameters			TRMM estimation is more or less same as ECMWF	ECMWF estimation (rain frequency) is over estimated	Rain events are estimated better in ECMWF	TRMM estimation gives less false detection	"No rain" events were estimated better in TRMM	"Rain" events were more correctly estimated in ECMWF	"Rain" events are correct multiple times than the 'Rain" events are incorrect in Both cases

From the yes/no dichotomous verification method, it is found that both TRMM and ECMWF rainfall data sets may be used in hydrological design. However, ECMWF rainfall data would be safe to use for flood forecasting purposes but might generate a false flood warning due to overestimates of rain events. In case of TRMM, rainfall data chances of missing a flood event are higher.

Table 4.5 shows the results of the continuous variables verification methods. Methods for estimation of continuous variables verification describes the Additive Bias (i.e mean error), Multiplicative Bias, Correlation Coefficient and Skill Error of both the ECMWF and TRMM RF data series. These parameters show better accuracy for TRMM rainfall data than that of ECMWF data. But, coefficient of correlation and skill scores show that both sets of data have less agreement with the observed data in all stations during both the years.

Table 4.5: Evaluation of ECMWF and TRMM daily RF time series by continuous variables verification methods

Station	Year	Data Type	Continuous variables statistics			
			ME	Bias	r	SS
Rangpur	2004	TRMM	1.08	0.85	0.36	-0.08
		ECMWF	1.52	0.80	0.16	-0.20
	2006	TRMM	0.68	0.85	0.34	-0.16
		ECMWF	0.80	0.83	0.39	0.12
Dinajpur	2004	TRMM	0.65	0.89	0.32	-0.34
		ECMWF	1.09	0.83	0.23	-0.16
	2006	TRMM	0.09	0.97	0.43	-0.09
		ECMWF	0.03	0.99	0.40	0.08
Sylhet	2004	TRMM	3.59	0.69	0.25	-0.25
		ECMWF	4.52	0.61	0.23	-0.13
	2006	TRMM	4.41	0.55	0.30	-0.03
		ECMWF	4.18	0.57	0.28	-0.03
Evaluation of the Statistical Parameters			TRMM Estimation contains less mean error	Average Forecast magnitude is better in TRMM Estimation	TRMM Estimation shows better Correlation Coefficient	ECMWF shows better results

4.4 Conclusions

ECMWF and TRMM rainfall data have been downloaded and evaluated for their potentiality in flood studies using the observed rainfall data of the years 2004 and 2006 for Dinajpur, Rangpur and Sylhet stations in Bangladesh. The visual verification, yes/no-dichotomous verification and continuous variables verification methods have been used. The results indicate that both ECMWF and TRMM have potential for use in flood studies.

The ECMWF provides the rainfall data in advance and hence can be used in flood forecasting studies to increase the forecast lead time. Both ECMWF as well as TRMM rainfall data may be used in flood estimation studies where observed rainfall data are not at all available. However, such studies should be taken up with more number of stations and more length of data to develop the relationships between observed rainfall and estimated rainfall by ECMWF or TRMM. The supremacy of either of the methods of rainfall estimation over the other could not be established. The ECMWF forecasted rainfall data have been used in Jamuneswari Flood Forecasting System (JFFS) for augmentation of lead time.

Chapter 5 - Development of Jamuneswary Flood Forecasting System

5.0 Introduction

Bangladesh is a flood prone country and various structural and non-structural measures have been adopted to minimize the flood losses. The present system of flood forecasting and early warning is not satisfactory because of a number of reasons such as limited lead time of forecasts, outdated dissemination networks, and lack of direct feedback from the end-users. Hence, in the present study, a methodology for flood forecasting system based on forecasted rainfall and different modules of MIKE11 software has been developed to increase the lead-time and accuracy of forecasts. The methodology has been applied to develop an operational flood forecasting system for Jamuneswari river catchment. The details of the data used, its processing and analysis, catchment modeling using MIKE11 Rainfall-Runoff (NAM: Nedbor-Afstromnings-Model) and Hydrodynamic (HD), increasing of forecast lead-time and accuracy using MIKE11-Flood Forecasting (FF) module and inputting of ECMWF forecasted rainfall are presented in this chapter. The developed system has been named as the Jamuneswari Flood Forecasting System (JFFS).

5.1 Data collection and processing for JFFS

To develop the JFFS, required hydro-meteorological and survey data have been collected from BWDB. Data is the important part of advance hydrologic modeling and forcasting (Sivakumar and Berndtsson, 2010; Ojha et al., 2008), After the collection of data from BWDB, necessary quality checks were performed (Rahman et al., 2010a). In the JFFS area, BWDB maintains 15 rainfall stations, 3 evaporation stations, 2 gauges, and discharge measurement stations and two water level stations. The cross sections for all the rivers and tributaries within the JFFS catchment were collected from Flood Forecasting and Warning Centre (FFWC). The river network and catchment boundary were delineated from 90m SRTM DEM data (Chapter 3). The basic input of the rainfall-runoff model of JFFS is rainfall data. Daily point rainfall data of 15 ordinary rain gauges (Figure 2.1 of Chapter 2) maintained by BWDB were used to calculate the mean areal rainfall for the catchments of the model area. Forecasted rainfall were obtained from ECMWF data as discussed elaborately in Chapter 4.

In the rainfall data, there were huge gaps as shown in Appendix 5.1. The gaps were filled up using the data from neighboring stations (Appendix 5.2). Arithmetic mean, normal ratio and distance power methods were used for gap filling and for each method relative bias (R_b) was computed. Finally, the gaps were filled up using the method which gave minimum bias.

Daily water level data of Badarganj and Chak-Rahimpur stations were checked for their consistency using multi-station time series plots and double mass curve analysis. The data of both the stations were found to be consistent.

5.2 Development of JFFS using MIKE11

The Jamuneswari Flood Forecasting System (JFFS) has been developed using MIKE11. MIKE11 has been used by other researchers also. Some of the earlier studies, especially for this region are summarised below.

Paudyal (2002, 2002a) described MIKE11 NAM, HD, and FF model for simulation of complex river system in Bangladesh to develop Flood Forecasting and Warning System and found it to be very promising in building the flood-preparedness system. Patro et al. (2009) calibrated the one dimensional model MIKE11 for the monsoon period in the delta region of Mahanadi River basin in India and found that the model performs quite satisfactorily in simulating the river flow for the delta region of Mahanadi river basin. Mishra et al. (2001 and 2005) applied Hydraulic modeling for optimization of water level and discharge measurement. Markar et al. (2004) evaluated Info-Works, HEC-RAS (Hydrologic Engineering Centers River Analysis System) and MIKE11 HD model to assess the suitability for integration into the Flood Forecasting System (FFS) with criteria of accuracy, technical capability and ability to interface with customized FFS. After a preliminary evaluation, InfoWorks and MIKE11 were found capable of satisfying the accuracy. They also mentioned that the model run times for MIKE11 were much smaller and the stability of MIKE11 runs was less sensitive to specified initial conditions. MIKE11 was found to be more suited for Flood Forecasting System of Yangtze river in China by Markar et al. (2004). During ever highest flood of 1998 in Bangladesh, Flood Forecasting and Warning Center (FFWC) of BWDB prepared daily flood bulletin for 24 and 48 hr in advance using MIKE11 NAM, HD, and FF model.

Flow chart for development of Flood Forecasting System is given in Figure 5.1. MIKE11 is a dynamic modeling tool for rivers and channels based on graphical user interface MIKE Zero. MIKE Zero is windows based software integrated with the computational core of the precious MIKE11 generation, which includes graphical editing facilities and improved computational speed gained by the full utilization of 32-bit technology. Geometric inputs like river network, river cross sections, etc. are imported from GIS environment to MIKE11 environment.

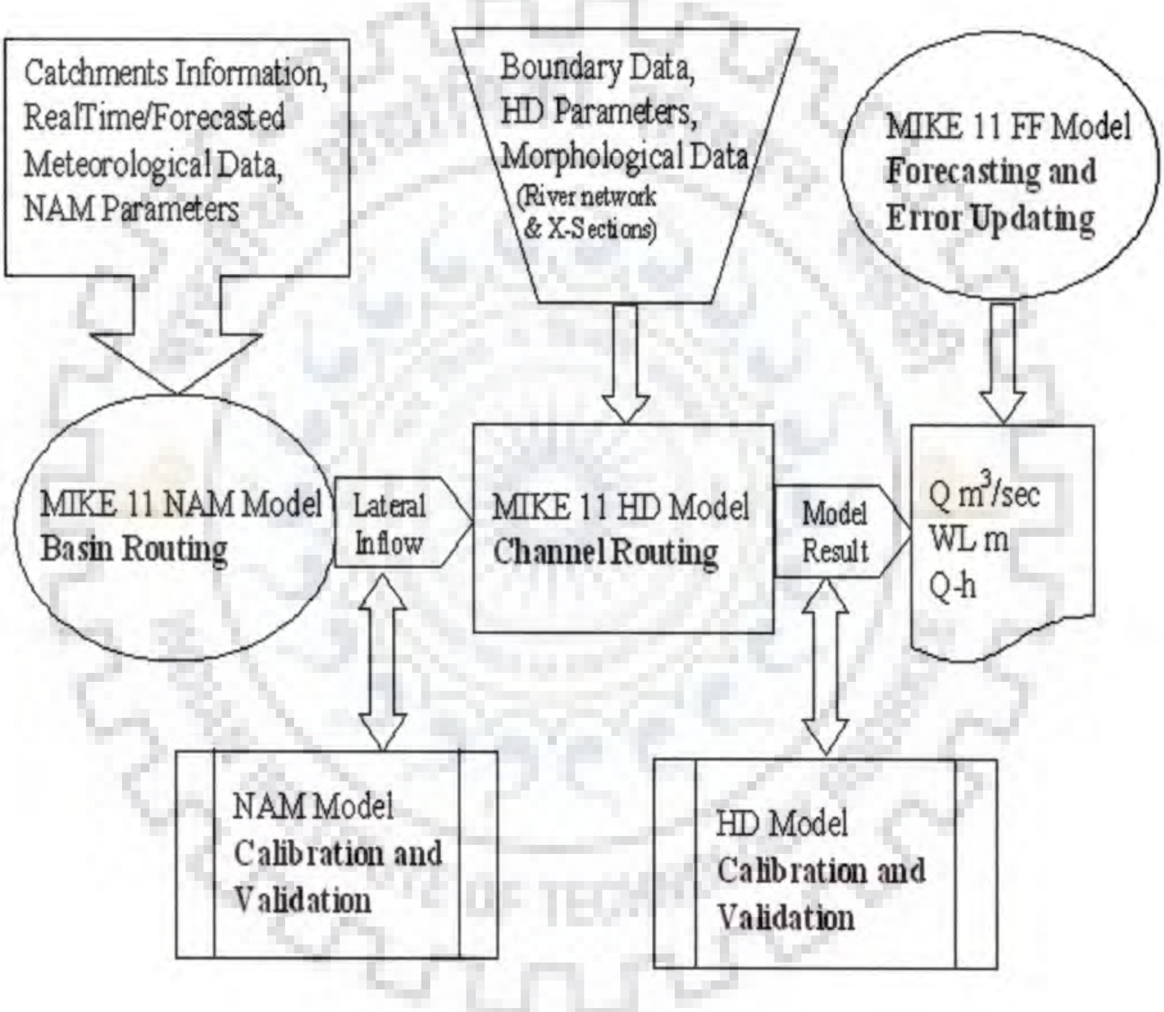


Figure 5.1: Flow chart for development of flood forecasting system

MIKE11 contains various modules like Hydrodynamic (HD), Advection-Dispersion (AD), Sediment Transport (ST), ECO Lab (Including Water Quality modeling etc), Rainfall-Runoff (RR), Flood Forecasting (FF), Data Assimilation (DA) and Ice modeling (DHI, 2004). This software is being used to solve various water engineering problems like irrigation water management, flood management, etc. In this study, RR, HD, and FF modules have been used to compute the flood flow and stages at different locations in the Jamumeswari-Karatoya river system.

5.2.1 Rainfall-runoff (MIKE11-NAM) module

The MIKE11 RR model contains five different types of RR modules such as Unit Hydrograph Module (UHM), which includes different loss models (constant, proportional) and the SCS method for estimating storm runoff; Soil moisture accounting module ; Urban module having two methods A) Time/area Method and B) Non-linear Reservoir (kinematic wave) Method; Flood Estimation Handbook (FEH), a method for flood estimation in the UK and NAM (the abbreviation of the Danish "Nedbor-Afstromnings-Model") module.

Among the different types of Rainfall-Runoff model specified in MIKE11, the NAM method has been selected for this study. This model was originally developed by Nielsen and Hansen (1973). NAM model is a well-proven engineering tool that has been applied to a number of catchments around the world, representing many different hydrological regimes and climatic conditions (Refsgaard and Knudsen, 1997).

The NAM model is characterized as a deterministic, conceptual, lumped type of model with moderate input data requirements. NAM is a mathematical hydrological model comprising a set of linked mathematical statements representing various components of the rainfall-runoff process in catchments by continuously accounting for the moisture content in four different and mutually inter-related storages that represent different physical elements of the catchment. These storages are (i) snow storage, (ii) surface storage, (iii) lower or root zone storage, and (iv) ground water storage.

5.2.1.1 Description of NAM model structure

NAM simulates four different and mutually interrelated storages that represent different physical elements of the catchment. These storages are snow storage, surface storage, lower or root zone storage, and groundwater storage. In this study snow storage has not been considered. NAM produces catchment rainfall-runoff and information of temporal variation of the evapotranspiration, soil moisture content, groundwater recharge, and groundwater levels. The resulting catchment runoff is split conceptually into overland flow, interflow, and base flow components. The model structure is shown in Figure 5.2. The components of the NAM model structure are described below.

Rainfall intercepted on the vegetation and trapped in depressions or cultivated part of the ground is known as surface storage, U. U_{max} denotes the upper limit of the surface storage. The surface storage, U, is continuously diminished by evaporative consumption, E_p and horizontal interflow. When there is maximum surface storage, some portion of water flows as excess runoff, P_N, as overland flow, QOP, and some portion of water infiltrates into the lower zone or root zone, DL, and groundwater storage, G. L_{max} denotes the upper limit of the amount of water in this storage. Moisture in the lower zone storage is subject to consumptive loss from transpiration. The moisture content controls the amount of water for groundwater recharge, interflow, QIP, and overland flow components.

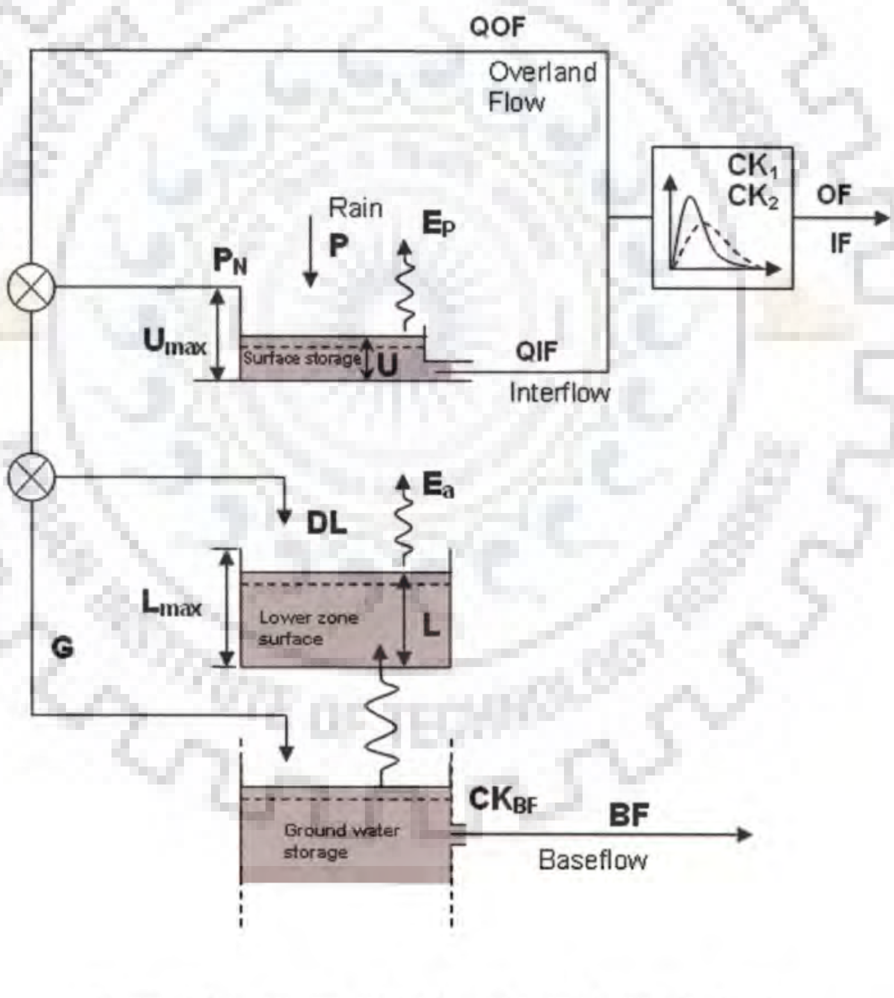


Figure 5.2 Structure of the NAM model used in JFFS

The water in surface storage, U, satisfy the potential evapotranspiration, E_p, demand. When $U < E_p$ then the shortage of potential evapotranspiration is assumed to be withdrawn by root activity from the lower zone storage, L, at an actual rate of evapotranspiration E_a which is proportional to, E_p, and varies with the relative soil moisture content, L/L_{max}, of the lower zone storage (5.1).

$$E_a = (E_p - U)\frac{L}{L_{max}} \qquad (5.1)$$

When $U > U_{max}$, then the excess water P_N gives rise to overland flow and increases the infiltration. The overland flow is denoted by QOF, is proportional to P_N and vary linearly with the relative soil moisture content, L/L_{max}, of the lower zone storage.

$$QOP = CQOF(L/L_{max} - TOF)/(1-TOF)P_N \quad \text{for } L/L_{max} > TOF \qquad (5.2)$$
$$= 0 \quad \text{for } L/L_{max} \le TOF$$

Where, $CQOF$ is the overland flow runoff coefficient ($0 \le CQOF \le 1$)

TOF is the threshold value for overland flow ($0 \le TOF \le 1$).

Some portion of excess water, P_N, does not run off as overland flow and infiltrates into the lower zone storage. This portion of excess water, ΔL, of the water available for infiltration, (P_N -QOF), is assumed to increase the moisture content L in the lower zone storage. The remaining amount of infiltrating moisture, G, is assumed to percolate deeper and recharge the groundwater storage.

The interflow, QIF, is assumed to be proportional to U and also it varies linearly with the relative moisture content of the lower zone storage (5.3).

$$QIF = CKIF(L/L_{max} - TIF)/(1-TIF)U \quad \text{for } L/L_{max} > TIF \qquad (5.3)$$
$$= 0 \quad \text{for } L/L_{max} \le TIF$$

Where $CKIF$ is the time constant for interflow, and TIF is the root zone threshold value for interflow ($0 \le TIF \le 1$).

The interflow, CK, is routed through two linear reservoirs in series with the same time constant CK_{12}. The overland flow routing is also based on the linear reservoir concept but with a variable time constant.

$$CK = \begin{cases} CK_{12} & for OF < OF_{min} \\ CK_{12}\left(\frac{OF}{OF_{min}}\right)^{-\beta} & for OF \ge OF_{min} \end{cases} \qquad (5.4)$$

Where, OF is the overland flow (mm/hour), OF_{min} is the upper limit for linear routing (= 0.4 mm/hour), and β = 0.4. The constant β = 0.4 corresponds to the Manning's formula for modeling the overland flow. Equation (5.2) ensures in practice that the routing of real surface flow is kinematic, while subsurface flow being interpreted by NAM as overland flow (in catchments with no real surface flow component) is routed as a linear reservoir.

The amount of infiltrating water, G, recharging the groundwater storage depends on the soil moisture content in the root zone.

$$G = \begin{cases} (\mathrm{P_N} - QOP)\dfrac{L/L_{\max} - TG}{1 - TG} & for L/L_{\max} > TG \\ 0 \; for L/L_{\max} \leq OF_{\min} & \end{cases} \tag{5.5}$$

Where, TG is the root zone threshold value for groundwater recharge ($0 \leq \mathrm{TG} \leq 1$).

The lower zone storage represents the water content within the root zone. After apportioning the net rainfall between overland flow and infiltration to groundwater, the remainder of the net rainfall increases the moisture content L within the lower zone storage by the amount ΔL.

$$\Delta L = P_N - QOP - G \tag{5.6}$$

The baseflow, BF, from the groundwater storage is calculated as the outflow from a linear reservoir with time constant $CKBF$.

5.2.1.2 Data requirements for MIKE11 NAM model

NAM model needs rainfall and potential evapotranspiration data, initial conditions (relative water contents of surface and root zone storage, values of overland flow and interflow and values for baseflow) and model parameters (catchment characteristic). For flood forecasting in the monsoon period, irrigation, and ground water intervention are negligible and only rainfall and evaporation are the dominating inputs. Hereinafter the rainfall and potential evapotranspiration are described elaborately. Data required (temperature and radiation) for snow modeling are not described because of its irrelevance in this study.

Rainfall (mm): Time steps of the rainfall data series depends on the type of studies and the required time steps of the model output. The daily rainfall values are applicable where runoff or flood response is delayed. In the rapidly responding catchments where accurate peak flows are required, hourly rainfall data may be required. Any time steps can be the rainfall input.

The NAM model is capable of making the necessary interpolations according to the simulation time step. The unit of rainfall data should be in millimeter.

Potential evapotranspiration (mm): Monthly values of potential evapotranspiration are usually sufficient. Only minor improvements can be obtained by specifying daily values instead of monthly values. The unit of evapotranspiration should also be in millimeter.

Discharge (m^3/sec): To compare the model result, discharge time series at the catchment outlet is required for model calibration and validation.

Mean area weighting: In a lumped method, meteorological data from different points or stations within a single catchment or subcatchment are required to be combined into a single time series of weighted averages. The resulting time series will represent the mean area values of rainfall and potential evapotranspiration for a catchment. The weights can be determined by the Thiessen method using GIS software.

Different time steps: Rainfall data are some times available in the same station in the form of different time steps e.g. both daily and hourly stations, then the distribution in time of the average catchment rainfall may be determined using a weighted average of the high-frequency data collection stations.

5.2.1.3 NAM model setup

The whole process of MIKE11 NAM has been described in the subsequent sections. The procedures for catchment delineation, cross sections, boundary condition, rainfall-runoff, and hydrodynamic parameter files are presented.

Catchment Boundaries Delineation: The catchments boundaries in the JFFS have been delineated from 3 arc-sec 90 meter Digital Elevation Module (DEM) provided by Shuttle Radar Topography Mission (SRTM) using hydrology tool of special extension of Arc-GIS software. Figure 5.3 shows the delineated catchment of JFFS. The catchment has been divided into two parts i.e. upper catchment and lower catchment on the basis of ground slope and soil permeability.

Upper Catchment (Catch 1): These areas consist of fast responding catchments due to steep ground slope and highly permeable soil. Time constants for overland flow routing (CK_1, CK_2) and time constant for interflow (CKIF) values are low whereas specific yield and infiltration rates are high.

Lower catchment (Catch-2): Compared to upper sub-region the topography of this sub-region is flatter and soil is less permeable. Time constants CK_1, CK_2 and CKIF values are high though specific yield and infiltration rates are low.

Discharge Basin: Both catchments are grouped into one discharge basin, so that their drainage outlets are regular discharge measuring stations. The basin outlet location of the C.Jamuneswari-Karatoya river is at Chalk Rahimpur.

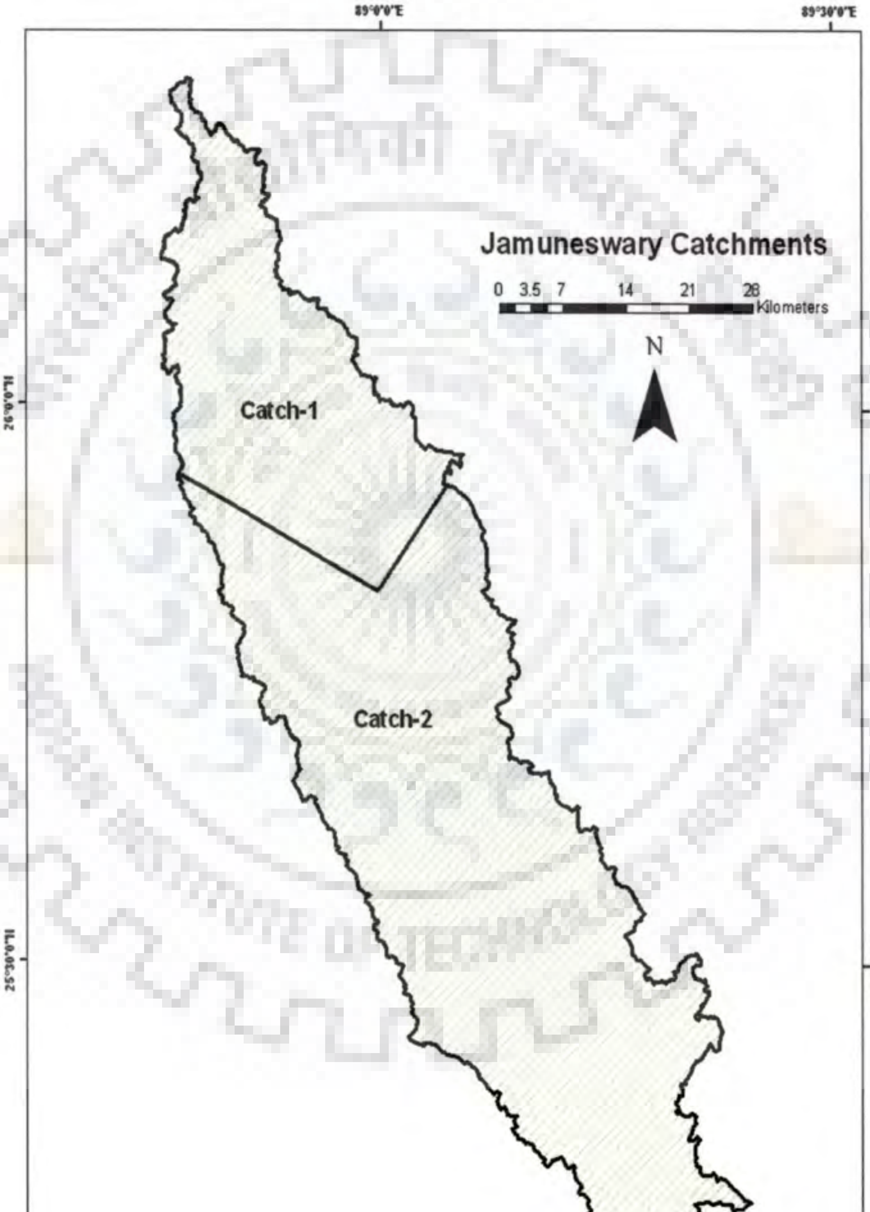


Figure 5.3: Jamuneswari catchment has been divided in two parts as Catch-1 (upper catchment) in the north and Catch-2 (lower catchment) in the south.

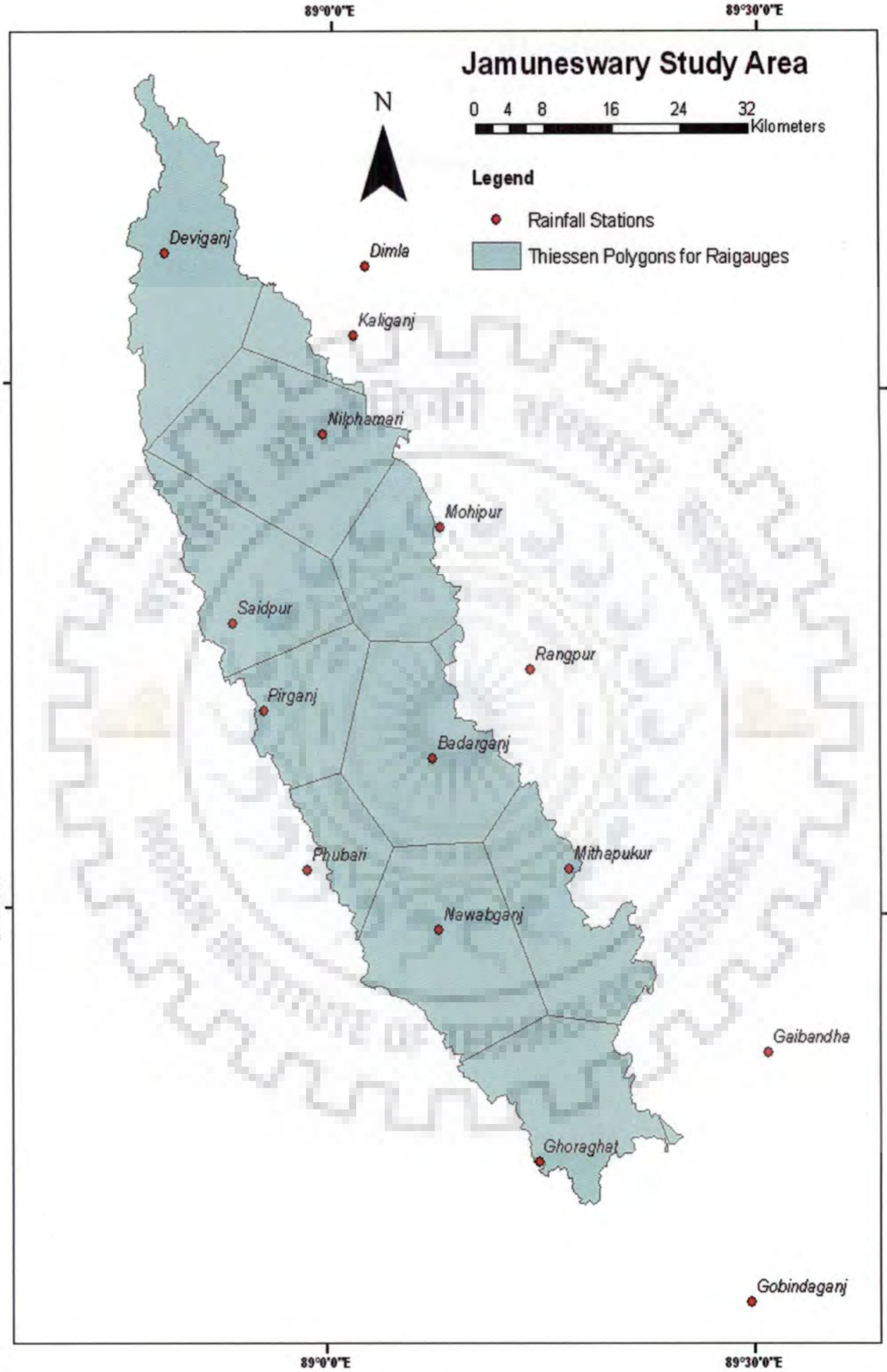


Figure 5.4: Thiessen polygons of different rainfall stations

Mean Areal Rainfall: Thiessen weights of 15 rainfall stations for JFFS catchments are determined using ArcGIS 9.3 spatial analyst (Figure 5.4 and Table 5.1). From the Table 5.1 it is found that the stations Dimla, Gaibandha, and Gobindaganj are having less significant thiessen weightages over the catchment and thus have been excluded from the study. The mean areal rainfalls are then calculated from the available data of 12 point rainfall stations.

Table 5.1: Area and weightage of rainfall Thiessen polygons of JFFS catchments

Sl No	Rainfall stations	Area of Thiessen polygon in km²	Weightage	Remarks
1	Debiganj	330.91	0.128	
2	Dimla	0.06	0.000	Excluded because no significant weightage
3	Kaliganj	54.67	0.021	
4	Nilphamari	364.62	0.141	Inconsistent Data and can be replaced by average of Debiganj and Kaliganj
5	Mohipur	180.94	0.070	
6	Rangpur	9.16	0.004	
7	Saidpur	262.57	0.101	Inconsistent Data can be replaced by average of Mohipur and Pirganj
8	Pirganj	169.43	0.065	
9	Badarganj	305.05	0.118	
10	Phulbari	99.01	0.038	Inconsistent Data and can be replaced by average of Pirganj and Nawabganj
11	Mithapukur	242.61	0.094	
12	Nawabganj	326.17	0.126	
13	Gaibandha	3.25	0.001	Excluded because no significant weightage
14	Ghoarghat	244.41	0.094	Data Inconsistent and can be replaced by average of Gaibanda and Nawabganj
15	Gobindaganj	0.00	0.000	Excluded because no significant weightage
	Total	**2592.85**	**1.00**	

The upper catchment, Catch-1 and lower catchment, Catch-2 have been rearranged after the exclusion of stations having the insignificant weightage over the area as shown in the Table 5.2.

Mean Areal Evapotranspiration: Weightage factors of six evapotranspiration stations for JFFS catchment are determined by Thiessen polygon method using ArcGIS 9.3 spatial analyst (Figure 5.5). Mean areal evapotranspiration weightage factors of three evapotranspiration stations for 2 subcatchments are defined by considering influence of neighboring stations (Table 5.3). The mean areal evapotranspiration are calculated, for the period 2003 to 2005, from the available data of three point evapotranspiration stations using the thiessen polygons.

Table 5.2: Rearrangement of weightage of rainfall thiessen area of Catch-1 and Catch-2

Sl No	Subcatchment	Rainfall stations	Area of Thiessen polygon in km²	Weightage
1	Catch-1 (Upper Catchment)	Debiganj	330.970	0.441
2		Kaliganj	54.670	0.073
3		Nilphamari	364.620	0.486
		Total	**750.260**	**1.000**
1	Catch-2 (Lower catchment)	Mohipur	180.930	0.098
2		Rangpur	9.160	0.005
3		Saidpur	262.570	0.143
4		Pirganj	169.430	0.092
5		Badarganj	305.050	0.166
6		Phulbari	99.010	0.054
7		Mithapukur	242.610	0.132
8		Nawabganj	326.170	0.177
9		Ghoarghat	247.660	0.133
		Total	**1842.590**	**1.000**
Total Area = Catch-1 + Catch-2 =			**2592.85**	

Table 5.3: Area and weightage of evaporation thiessen area of Catch-1 and Catch-2

Evaporation stations	Catch-1		Catch-2	
	Area	Weightage	Area	Weightage
Ruhea	750.26	1	196.78	0.11
Rangpur	0.00		128.93	0.07
Dinajpur	0.00		1516.88	0.82
Total	**750.26**	**1**	1842.59	1.00

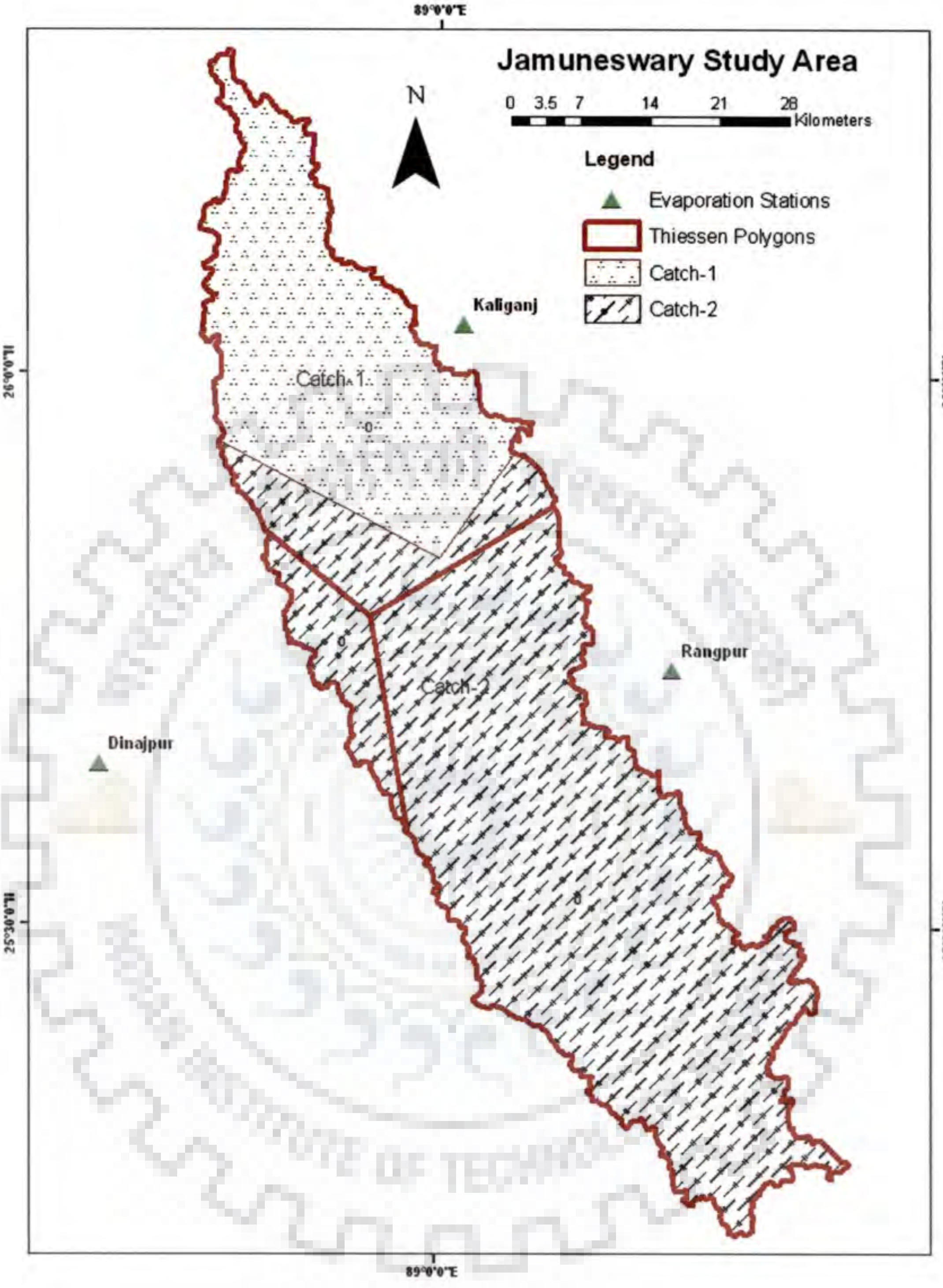


Figure 5.5: Thiessen polygons of evapotranspiration stations

5.2.1.4 Calibration of NAM parameters

The model parameters have been determined by manual calibration process after several simulations. Model has been calibrated with the observed discharge at Chak-Rahimpur. To save time and for the ease of comparison only one year i.e., 2003 data has been considered for calibration of NAM parameters.

The calibration process starts with the water balance adjustment. The water balance should be formulated by total evapotranspiration equal to net precipitation minus runoff. The evapotranspiration will increase with increasing the maximum surface storage, U_{max} and root zone storage, L_{max}. The peak volume is adjusted by changing the overland flow runoff coefficient (*CQOF*) and the shape of the peak depends on the time constant used in the runoff routing (CK_{12}).

Decrease in the overland flow or interflow will result in a higher baseflow. The shape of the baseflow recession is a function of the baseflow time constant (*CKBF*). The root zone threshold value of overland flow, *TOF,* threshold value of interflow, *TIF,* and threshold value of ground water recharge, *TG* are considered to be zero in the beginning of the calibration. These threshold values adjust fine-tuning of simulation result after initial calibration using U_{max}, L_{max}, *CQOF*, CK_{12}, and *CKBF*.

During the calibration, a trial-and-error parameters adjustment have been made until satisfactory results are obtained to minimize the uncertainty. The calibrated parameters that mostly affect (DHI, 2004) the processes are described in Table 5.4 along with the adapted values and the range of lower to higher values.

Tabel 5.4: Calibrated values of mostly affected NAM model parameters.

Parameters	**Range of lower to higher values**	**Adapted values**	
		Catch-1	**Catch-2**
Maximum amount of surface storage, U_{max}	5-35 mm	33	35
Maximum moisture contents of root zone storage, L_{max}	50-400 mm	140	160
Overland flow coefficient, CQOF	0-1	0.80	0.80
Time constant for interflow, CKIF	200-2000 mm	600	700
Time constant for routing base flow, CKBF	500-5000 hours	1500	2000
Time constant for routing overland flow, $CK_{1,2}$	3-72 hours	124	124
Root zone threshold value for overland flow, TOF	0-0.9	1	1.65
Root zone threshold value for inter flow, TIF	0-0.9	0.00	0.50
Root zone threshold value for recharge, TG	0-0.9	0.80	0.50

5.2.1.5 Validation of NAM model

Validation of the NAM model of JFFS has been done for the monsoon period from 2003 to 2005. These monsoon periods have been considered on the basis of the data quality of the observed data as analyzed herein before. Validation of rainfall-runoff model has been made with the help of available discharge, available from rating curve corresponding to the observed river stage at Chak-Rahimpur, the outlet point of the model area.

5.2.1.6 Uncertainty in NAM model

For hydrologic forecasting purpose, input data for this model are not always completely available and model structures are under hypothetical assumptions of the underlying natural processes; therefore, model parameters need to be calibrated. This uncertainty includes errors corresponding to real time data collection and processing procedures, as well as the deficiencies (uncertainty) of the hydrological model parameter calibration, which transfer into forecast of discharge, water levels, and inundated areas. Many researchers tried to find out uncertainty in hydrological modeling in the recent past. Beven (1993), and Dhar and Majumdar (2009) addressed the issue of uncertainty in hydrological modelling. Bronstert and Bardossy (2003) tackled the problem of uncertainty arising from rainfall variability. Gabellani et al. (2007) investigated the propagation of uncertainty from rainfall to runoff. Benke et al. (2008), Butts et al. (2004), and Demeritt et al. (2007) described details about model uncertainty. Krzysztofowicz and Herr (2001) and Krzysztofowicz (2001) described the framework for an uncertainty processor for river stage forecasting. Under this study, uncertainty has been determined by calculation of different errors as described hereinafter.

The difference between an observed value and the forecasted value is called the error. To lower the error, the greater accuracy is required in computations. It is a difficult task to define the limits of acceptability of accuracy. One may speak of the average accuracy of the simulated values while another may be interested in the accuracy of the simulated values for a particular event or on a particular day. The validation process uses graphical and numerical performance measures. The graphical evaluation includes comparison of the simulated and observed hydrograph and discharges.

The scatter graph is a plot of the modeled result in the vertical axis verses observed data in the horizontal axis. If the model and observed data are in perfect match, then the point is plotted on a 45° line. The efficiency index (R^2) value is a measure of the degree of intensity of association between observation and model data. Efficiency index or the coefficient of determination (R^2) is a measure of goodness of fit. Though there are several studies available pertaining to performance evaluation of the model such as by Aitken (1973) and Fleming (1975), the method given by Nash and Sutcliffe (1970) is widely used in the area of hydrology and water resources for the detection of systematic errors with respect to long-term simulation.

The reliability of the MIKE11 NAM (and afterwards HD) has been evaluated on the basis of Nash and Sutcliffe efficiency index (R^2). The R^2 is given in equation (5.7)

$$R^2 = \frac{\sum_{i=1}^{n}(q_i - \bar{q})^2 - \sum_{i=1}^{n}(q_i - q_s)^2}{\sum_{i=1}^{n}(q_i - \bar{q})^2} \tag{5.7}$$

Where q_i = Observed flow at time *i* number of data points, $\bar{q}$ = Mean value of observed flow $= \frac{1}{n}\sum_{i=1}^{n} q_i$, q_s = Simulated flow at time *I*, n = Number of data points. R^2 can range from $-\infty$ to 1. A perfect match, corresponding to $R^2 = 1$, is not expected because of different error sources, including errors in meteorological input data, errors in recorded observations, errors in simplifications (assumptions) inherent in the model structure and errors due to the use of non-optimal parameter values.

An efficiency of 0 ($R^2 = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($R^2 < 0$) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the nominator in the expression above), is larger than the data variance (described by the denominator).

The number of parameters are calculated for each plot which provide further quantification analysis to support the assessment of overall reliability of the model. These are given below:

$$\text{Coefficient of correlation} = \frac{Cov(q_o, q_s)}{\sigma_{q_o}, \sigma_{q_s}} \tag{5.8}$$

Where $Cov(q_o, q_s)$ in the covariance of observed data and model result, σ_{q_o} and σ_{q_s} are standard deviations of the observed data and model data respectively.

Peak error = $\frac{q_{op} - q_{sp}}{q_{sp}}$ (5.9)

Volume error = $\frac{\sum_{i=1}^{n}(q_{o,i} - q_{si})}{\sum_{i=1}^{n} q_{o,i}}$ (5.10)

Peak time error = $T_{op} - T_{sp}$ (5.11)

Where, q_{op} = observed peak,

Q_{sp} = simulated peak,

$q_{o,i}$ = observed value at time step i,

$q_{s,i}$ = simulated value at step i,

T_{op} = time of observed peak,

T_{sp} = time of simulated peak and n= number of time steps

The time series and scatter plot of the model result versus observed discharge at Chak-Rahimpur are given in Figure 5.6. Time series plot is a qualitative measure of the goodness of fit, it is best indication of overall 'shape' of the model vs observed data and no other plot can demonstrate the time-varying behaviour of the model and observed data. The Table 5.5 shows the result contained errors with the validated model.

There are missing data in many rainfall stations. Moreover, due to inconsistency, data of some stations have been discarded for some particular period and replaced by data from nearby stations. Therefore, mean areal rainfall for those periods may differ from the actual situation. Again the model result has been compared with the discharge value computed from the rating curve. The rating curve has been validated with some uncertainty. So, these uncertainties contained with the results of rainfall–runoff model and the model results are also validated with some errors as shown in the Figure 5.6 and Table 5.5.

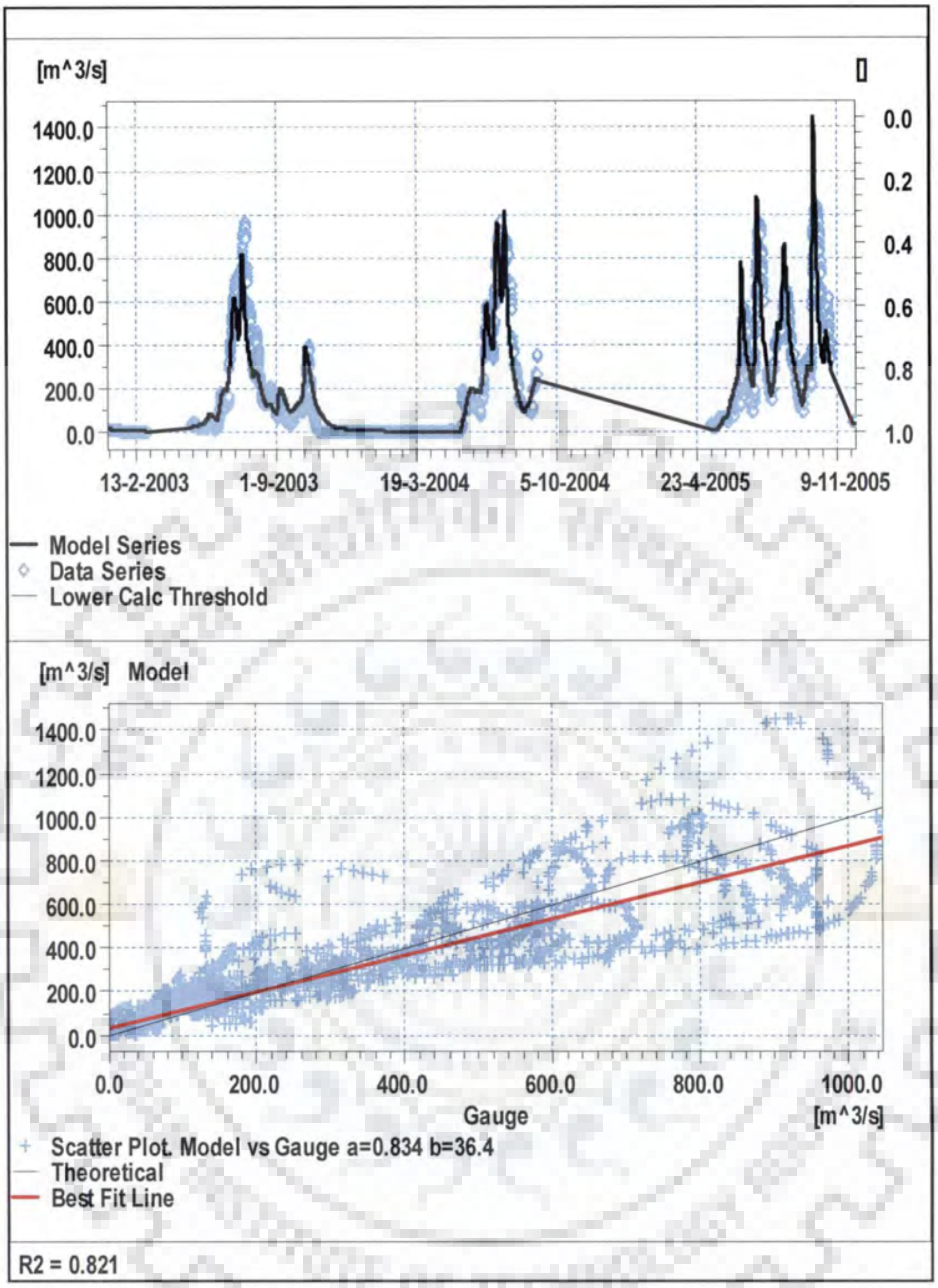


Figure 5.6: Time series and scatter plots of model result versus observed data

Table 5.5: Results of the validated NAM model

Description of model result	Result values
Efficiency index, R^2	0.821
Coefficient of correlation	0.91
Slope of scatter Plot, a	0.834
Peak error, %	19.25
Volume error, %	-7.92
Peak time error, Hours.	3.00

5.2.2 Hydrodynamic (MIKE11-HD) model

MIKE11 has a hydrodynamic module that solves the Saint-Venant's equation with an implicit finite difference method for the computation of flows in rivers. It can model sub-critical as well as supercritical flow conditions. MIKE11 HD applied with the dynamic wave description solves the vertically integrated equations of conservation of continuity and momentum, based on the following assumptions (DHI, 2004):

- The flow is one-dimensional; depth and velocity vary only in the longitudinal direction of the channel. This implies that the velocity is constant and the water surface is horizontal across any section perpendicular to the longitudinal axis.

- Water is incompressible and homogeneous; i.e., there is negligible variation in density.

- The bottom slope (of the channel) is small, thus the cosine of the angle with the horizontal may be taken as 1.

- The wavelengths are large compared to the water depth. This ensures that the flow everywhere can be regarded as having a direction parallel to the bottom. i.e., vertical accelerations can be neglected and a hydrostatic pressure variation along the vertical can be assumed.

- The flow is sub-critical (Supercritical flow may also be modeled in MIKE11 with more restrictive conditions).

The formulation can be applied to branched and looped networks and quasi two-dimensional (2-D) flow simulation on flood plains (Paudyal, 2002). Based on NAM calculated lateral inflow and additional inflow from external boundaries, the hydrodynamic module predicts water levels and reservoir inflows.

5.2.2.1 MIKE11 HD model setup

The model setup for the period of 2003-05 has been done for MIKE11 HD model given below step by step procedure.

River Network: To setup the HD Model, the river network of the river C.Jamuneswari (00 to 146.00 km), Bullai (00 to 38.675 km), Chikly (00 to 41.10 km), Kala (00 to 47.50 km), Akhira (00 to 39.50 km), and Karatoya (0.261 to 53.36 km) have been considered. Figure 5.7 shows the river network of the model and their chainages. The model network lies within the Bangladesh territory. The river CJamuneswari-Karatoya is the mainstream influenced during flood period by other tributary rivers, these have been considered in the river network. For the modeling purpose, flow direction is taken positive, maximum distance between two adjacent points (dx) is taken 1000 meter and the river type is taken as regular. Table 5.6 shows the detail of the branch connection of the river network.

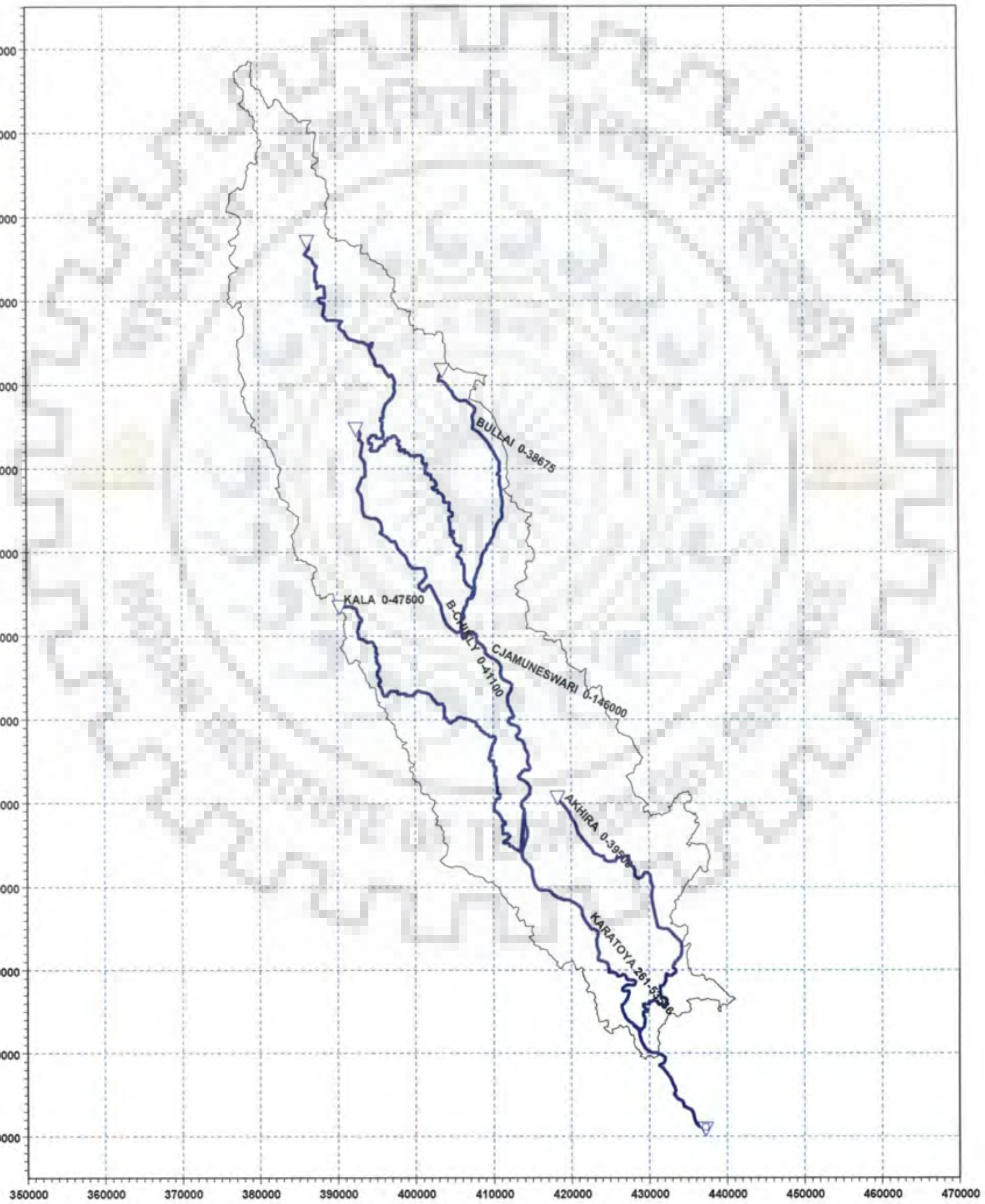


Figure 5.7: River network of MIKE11 HD model

Table 5.6: Detail of river network connection

Name of river	Upstream chainage	Downstream chainage	Upstream connected rivers	Chainage of connection	Downstream connected rivers	Chainage of connection
Akhira	0	39500			Karatoya	33750.00
B-Chikly	0	41100			CJamuneswari	100750.00
Bullai	0	38675			CJamuneswari	96400.00
CJamun eswaril	0	146000			Karatoya	261.00
Kala	0	47500			CJamuneswari	140000.00
Karatoy a	261	53536	C-Jamuneswari	146000		

River Cross Sections: The physical characteristics of the topography of the model domain area are described by cross-sections of the channel and flood plain. Mathematical expressions for cross-section were developed (DHI, 2004) in x-z co-ordinates, where x is the transverse distance from fixed point (left bank top) and z is the corresponding bed elevation. The equations (5.12) and (5.13) represent the conservation of mass and momentum, respectively, in a rectangular cross-section of horizontal bottom and constant width neglecting friction and lateral inflows, presented (DHI, 2004) as follows:

$$\frac{\partial(\rho Hb)}{\partial t} = -\frac{\partial(\rho Hb\bar{u})}{\partial x} \qquad (5.12)$$

$$\frac{\partial(\rho Hb\bar{u})}{\partial t} = -\frac{\partial\left(\alpha'\rho Hb\bar{u}^2 + \frac{1}{2}\rho gbH^2\right)}{\partial x} \qquad (5.13)$$

Where, ρ is the density, *H* the depth, *b* the width, $\bar{u}$ the average velocity along the vertical, and α' the vertical velocity distribution coefficient. Considering bottom slope S_b and varying width of channel, two more terms are added in the momentum equation (5.13) to form equation (5.14) which can project the flow direction of the reactions of the bottom and side-walls to the hydrostatic pressures.

$$\frac{\partial(\rho Hb\bar{u})}{\partial t} = -\frac{\partial\left(\alpha'\rho Hb\bar{u}^2 + \frac{1}{2}\rho gbH^2\right)}{\partial x} + \frac{\partial b}{\partial x}\frac{\rho gH^2}{2} - \rho gHbS_b \qquad (5.14)$$

$$= -\frac{\partial\left(\alpha'\rho Hb\bar{u}^{2}\right)}{\partial x} - b\frac{\partial\left(\frac{1}{2}\rho g H^{2}\right)}{\partial x} - \rho g H b S_{b}$$

Relationship of water level (h) and water depth (H) can be given by equation (5.15):

$$\frac{\partial h}{\partial x} = S_{b} + \frac{\partial H}{\partial x} \tag{5.15}$$

Solving the above equations, the conservation laws of mass equation and momentum equation become:

$$\frac{\partial (Hb)}{\partial t} = -\frac{\partial\left(Hb\bar{u}\right)}{\partial x} \tag{5.16}$$

$$\frac{\partial\left(Hb\bar{u}\right)}{\partial t} = -\frac{\partial\left(\alpha' Hb\overline{u^{2}}\right)}{\partial x} - Hbg\frac{\partial h}{\partial x} \tag{5.17}$$

These equations can be integrated to describe the flow through cross-sections of any shape when divided into a series of rectangular cross sections (DHI, 2004).

The number of cross sections should be sufficient to define adequately the variation in the channel shape along each model branch. The cross sections as taken in the year of 1998 by Bangladesh Water Development Board have been used in this study. A sample cross section at chainage 126m of C.Jamuneswari river is shown in the Figure 5. 8.

Boundary Conditions: The selection of boundary conditions depend on the availability of data and the physical situation of the model area. Boundary conditions could be a constant discharge from a reservoir; a discharge hydrograph of a specific event; constant water level e.g. in a large receiving water body; time series of water level e.g. tidal cycle; and a reliable rating curve, e.g. from a gauging station.

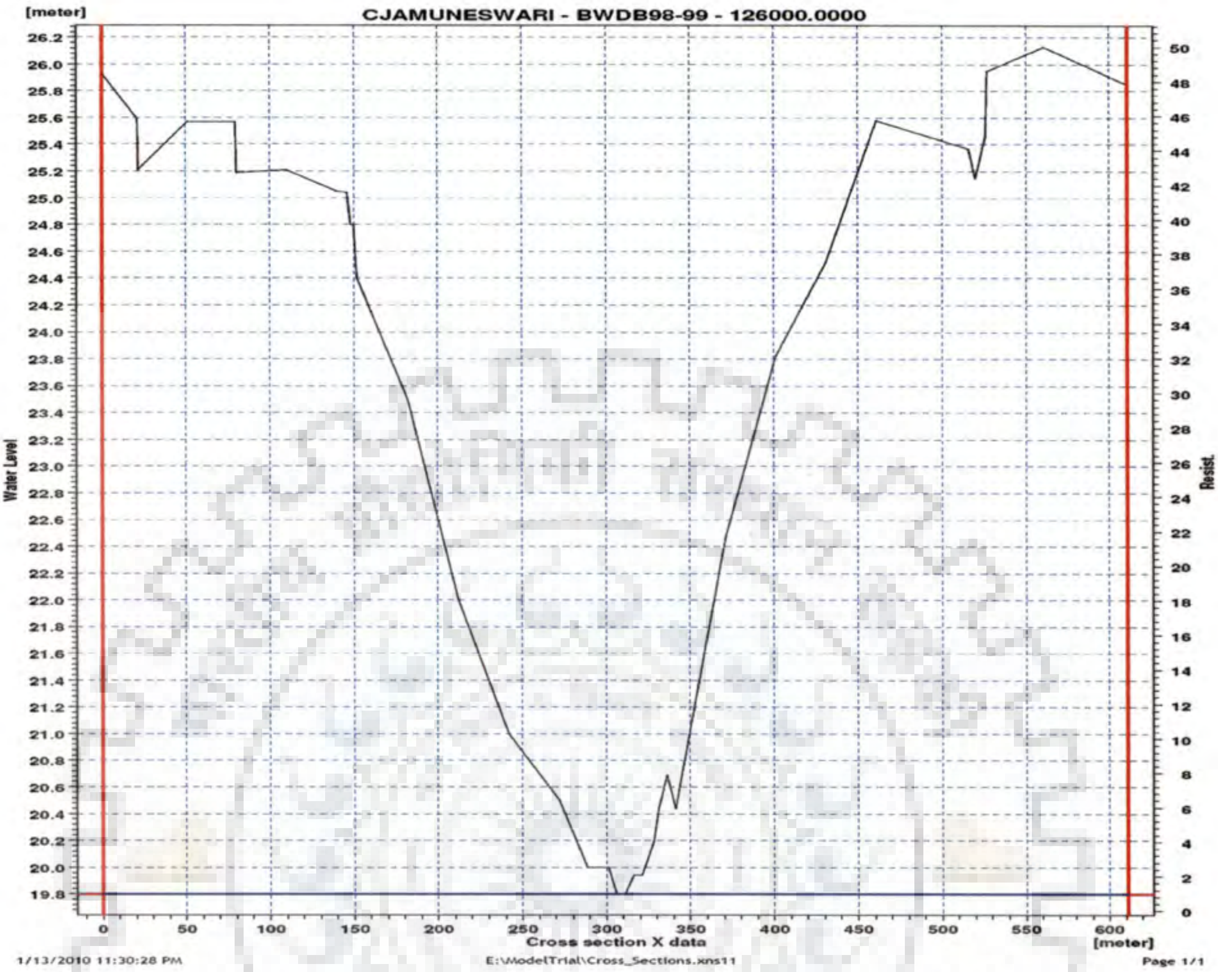


Figure 5.8: Cross section of Jamuneswari river at chainage 126.00 km

The *upstream boundary conditions* of river C.Jamuneswari, Bullai, Chikli, Kala, and Akhira are defined as arbitrary constant inflow, 1 m^3/sec. These rivers originate within the JFFS catchment area, where there are no gauge stations in the upstream of these rivers. The river Bullai, B-Chikli, Kala are connected with C.Jamuneswari at the downstream. C.Jamuneswari is connected with upstream of the Karatoya river. Karatoya is not required to define its upstream boundary conditions. The downstream of river Akhira is connected with Karatoya.

The *downstream boundary condition* of the C.Jamuneswari River has been taken as the Q-h relationship (i.e. rating curve), developed under this study for flood forecasting.

5.2.2.2 Integration of NAM with HD modules

NAM Model has been integrated with the HD modules to input the lateral inflow from two subcatchments to the river channels. Table 5.7 shows the reach lengths of six rivers connected with two subcatchments.

Table 5.7: Integration of subcatchments for lateral flows in the river channel

Subcatchments	Area (km^2)	River name	US Chainage (m)	DS Chainage (m)
CATCH-1	80	BULLAI	10	9000
CATCH-2	465	KALA	300	47500
CATCH-1	485	CJAMUNESWARI	10	85000
CATCH-2	250	CJAMUNESWARI	85001	105000
CATCH-1	226	B-CHIKLY	10	20000
CATCH-2	210	B-CHIKLY	20001	41100
CATCH-2	130	BULLAI	9001	38675
CATCH-2	375	AKHIRA	10	39500
CATCH-2	372	KARATOYA	361	53536

Simulation of NAM and HD Integration: Simulation period has been selected from May 01, 2003 to December 31, 2005 according to the data length and its consistency. For HD model, fixed time step of 10 minutes and the result of NAM model have been selected as hot start of initial condition of rainfall-runoff and the parameter file has been selected as the hot start of initial condition for HD Model. The computation of NAM and HD models give the time series of water level and discharge at each 1000 meters point with 10 minutes interval. The discharge and water level time series are generated at every alternate point. At the point of discharge generation, the rating curve or discharge-stage (Q-h) relation can be obtained.

Hydrodynamic (HD) Parameters: The C.Jamuneswari-Karatoya river is a tributary of the downstream Bangali river. The Bangali meets Jamuna near its confluence with the river Ganges, which carry the total discharges of Brahmaputra and Ganges basins to pass towards the Bay of Bengal. During peak discharge in the Jamuna and Ganges, normally during the month of August-September, the river Bangali gets some backwater effect and propagates towards Karatoya river. B-Chikly, Bullay, Kala, and Akhira are also rain-fed flashy rivers and they get some backwater effect from C.Jamuneswary-Karatoa main river stream of the JFFS catchment area i.e., the whole water body of the river network system of the study area changes over time and space. On the other hand, the average bed slope of the river Jamuneswari is 1:6500, Bullai is 1:4500, B-Chikly is 1: 3500, Kala is 1:9000, Akhira is 1:10500, and Karatoya is 1: 14000. The slope data indicate that the study area is flat. Hence, high order fully dynamic wave approximation has been considered to simulate the above river system. The global initial condition of water depth (h) has been taken as 10 m and the local initial condition for each river is also given in Table 5.8.

Bed resistance is the main calibration parameter for Hydrodynamic Model. MIKE11 allows two different types of bed resistance descriptions: (i) Chezy, and (ii) Manning. The Manning's M, equivalent to the Strickler coefficient, is inverse of conventional Manning's n. The value of n is typically in the range 0.01 (smooth channel) to 0.10 (thickly vegetated channel) and the corresponding values for M are from 100 to 10.

Table 5.8: Initial water depth for different river reach

River name	Chainage in meter	Initial h in meter
AKHIRA	0	20.5
AKHIRA	39500	16
B-CHIKLY	0	34
B-CHIKLY	41100	27.06
BULLAI	19000	34.35
BULLAI	30500	27.65
CJAMUNESWARI	100	50
CJAMUNESWARI	48950	40.25
CJAMUNESWARI	74250	32.3
CJAMUNESWARI	100750	27.6
CJAMUNESWARI	146000	22
KALA	0	25
KALA	7200	25
KALA	47500	24
KARATOYA	261	22
KARATOYA	53536	14.5

5.2.2.3 Calibration of integrated MIKE11 NAM-HD modules

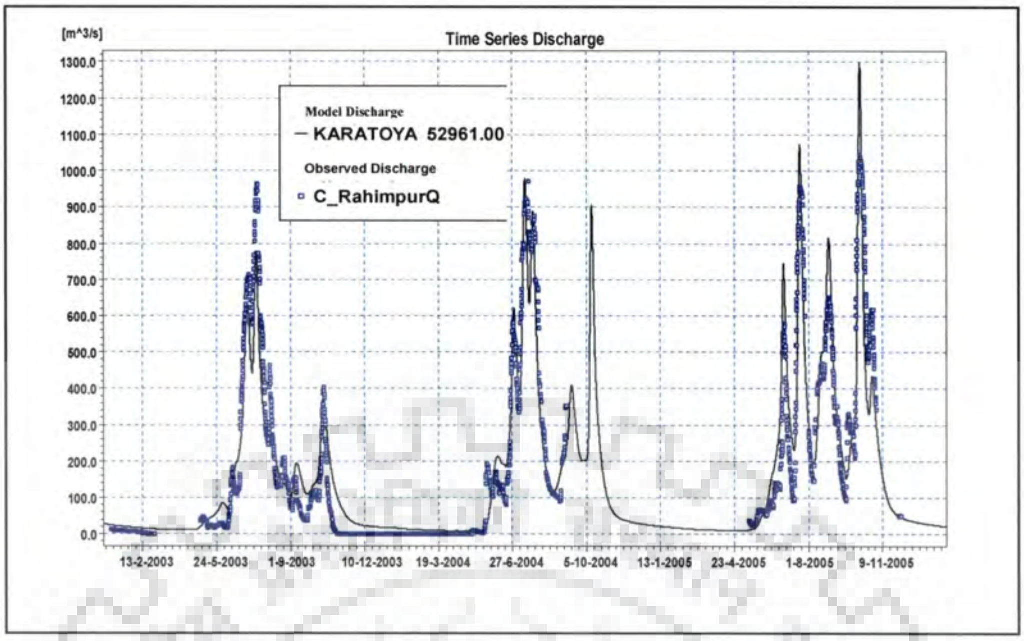
Several simulation runs have been done to calibrate the observed discharge at Chak-Rahimpur (Chainage 53.36 km in the river Karatoya). For calibration purpose the time period of 2003 have been considered. The calibrated values of Manning's M for each river are given in Table 5.9.

Table 5.9: Different values of Manning's 'M' or 'n' at different chainage of rivers.

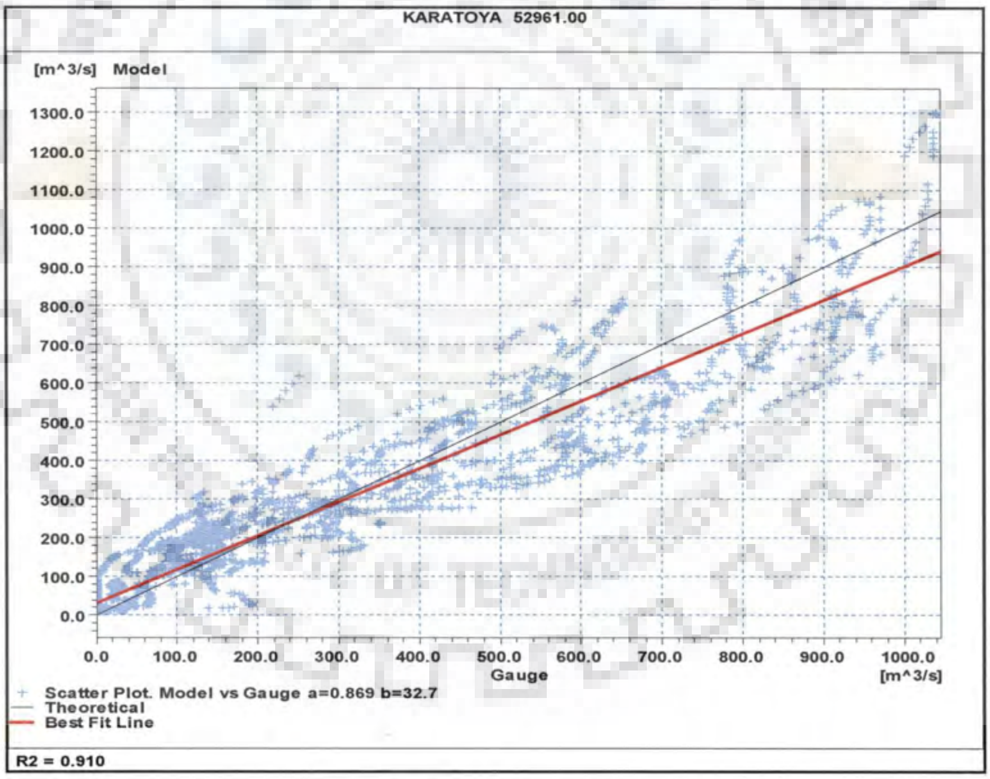
River name	Chainage in meter	Manning 'M'	Manning 'n'
BULLAI	0	21	0.048
BULLAI	30500	21	0.048
CJAMUNESWARI	0	21	0.048
CJAMUNESWARI	82000	21	0.048
CJAMUNESWARI	90000	22	0.045
CJAMUNESWARI	136000	22	0.045
KARATOYA	261	20	0.050
KARATOYA	53536	25	0.040
B-CHIKLY	0	21	0.048
B-CHIKLY	41100	22	0.045
AKHIRA	0	22	0.045
AKHIRA	39000	23	0.043
KALA	0	22	0.045
KALA	46000	25	0.040

5.2.2.4 Validation of integrated model

Validation of the MIKE11 HD model of JFFS has been performed over the period from 2003 to 2005. This three year period has been considered on the basis of quality of the observed data as analyzed in the previous sections. Observed river stage is available from 1988 to 2008 at Chak-Rahimpur. For validation purpose, discharge has been computed from rating curve corresponds to the observed river stage at Chak-Rahimpur, the outlet point of the model area. The Figures 5.9 and Figure 5.10 show the time series and scatter plot of model results corresponding to observed data for both discharge and river stage respectively at Chak Rahimpur. Discharge and stage values of HD and NAM model are compared to the observed values using various error coefficients and given in Table 5.10.



(a) Time Series plot



(b) Scatter plot

Figure 5.9: Time series (a) and scatter plot (b) of model versus observed discharge at Chak-Rahimpur (chainage 53 km of river Karatoya)

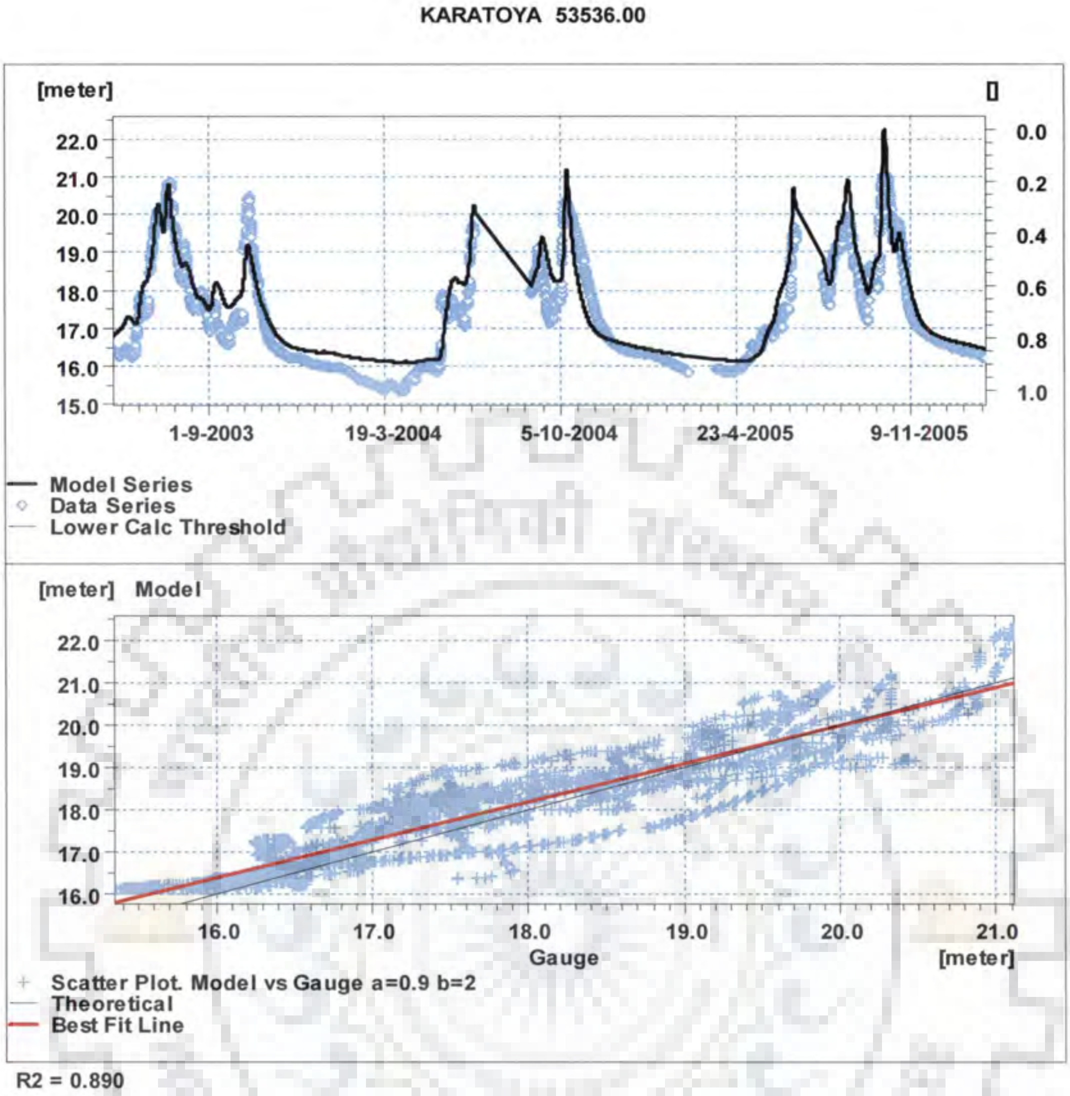


Figure 5.10: Time series and scatter plots of model versus observed river stgaes at Chak-Rahimpur

Table 5.10: Results for model discharges at Chak-Rahimpur after adding the HD model with the calibrated NAM model

Description of model result	**Results value for model discharge**	**Results value for model river stage**
Efficiency index, R^2	0.910	0.890
Slope of scatter plot, "a"	0.869	0.90
Coefficient of correlation	0.95	(0.94
Peak error %	14.32	5.04
Volume error %	-6.33	1.68
Peak time error Hrs	0.125	0.125

From data analysis, it has been found that the observed river stages at Chak-Rahimpur are consistent with the upstream river stage at Badarganj but there is some discontinuous measurement. From the validated hydrodynamic (HD) model results, it has been found that the errors in NAM model results are reduced as given in Table 5.11. It is worthy to mention that, rainfall data gave some uncertainty about 10.57% after filling the missing data. During MIKE11 NAM model calibration, it has been found that there exist some uncertainties with increasing extent which may be integrated from input data mainly from rainfall data and errors to calibrate the NAM parameters. However, MIKE11 HD model removed a portion of that uncertainty and improved the result by a significant amount.

Table 5.11 Improvement of result integrating HD module along with NAM module

Description of model result	Result using only NAM model	Result using both NAM and HD model	Result improved in percentage
Efficiency index, R^2	0.82	0.91	10.84
Slope of scatter plot, "a"	0.83	0.87	4.19
Coefficient of correlation	0.91	0.95	4.39
Peak error %	19.25	14.32	25.61
Volume error %	-7.92	-6.33	20.70
Peak time error hrs.	3.00	0.125	95.83

Observed discharge data in good quality are not available at Chak-Rahimpur, the outlet point of the JFFS catchment area. Then Q-h relation has been developed using old discharge data from 1989 to 1993. The collected river stages/water level data have been found quite consistent with the observed water level at Badraganj in the upstream of the Jamuneswari River. The recent discharge data at Chak-Rahimpur has then been generated from the corresponding water level at Chak-Rahimpur. The uncertainty has also been determined in the discharge relation curve at Chak-Rahipmour which may affect the model validation. The cross sections of the river network have been taken in the year of 1998 which might have some uncertainty and so the recent cross sections must give better result. Adopting modern measurement system, continuous collection of the real time data, increasing the frequency of discharge measurement, updatation of river cross-section, and precise tuning of parameters in MIKE11 NAM and HD model could provide improvement of the developed JFFS model results,.

5.2.2.5 Flood forecasting using JFFS with ECMWF input

The forecasted rainfall data of ECMWF for the year 2006 are available on the website in the form of text files. The 24-hour, 48-hour, and 72-hour forecasted rainfall have been used in the study for 24-, 48-, and 72-hour early flood forecasting using JFFS.

One major disadvantage of most of the operational flood forecasting system is that the forecasts are often issued without a probabilistic statement on the forecast value. Toward this, many investigators (Georgakakos, 1986; Puente and Bras, 1987; Bergman and Delleur, 1985) have quantified the uncertainty in the forecasted flood values. In this study, forecasted results for different lead-times were analyzed to determine the prevailing uncertainty and probabilistic statement is prepared in the conclusion.

The forecasted results for the period of 2006 have been compared with the real time forecasted values. The compared time series and scatter plots are given in the Figure 5.11 and the Table 5.12 provide the quantitative difference among the 24-, 48-, and 72-hour early forecasted and real time result of the JFFS. The graphical representation of the variation of efficiency index and coefficient of correlation is given in Figure 5.12. It is also found that the slope of 45° is being increased with respect to the increasing of peak time error given in Figure 5.13.

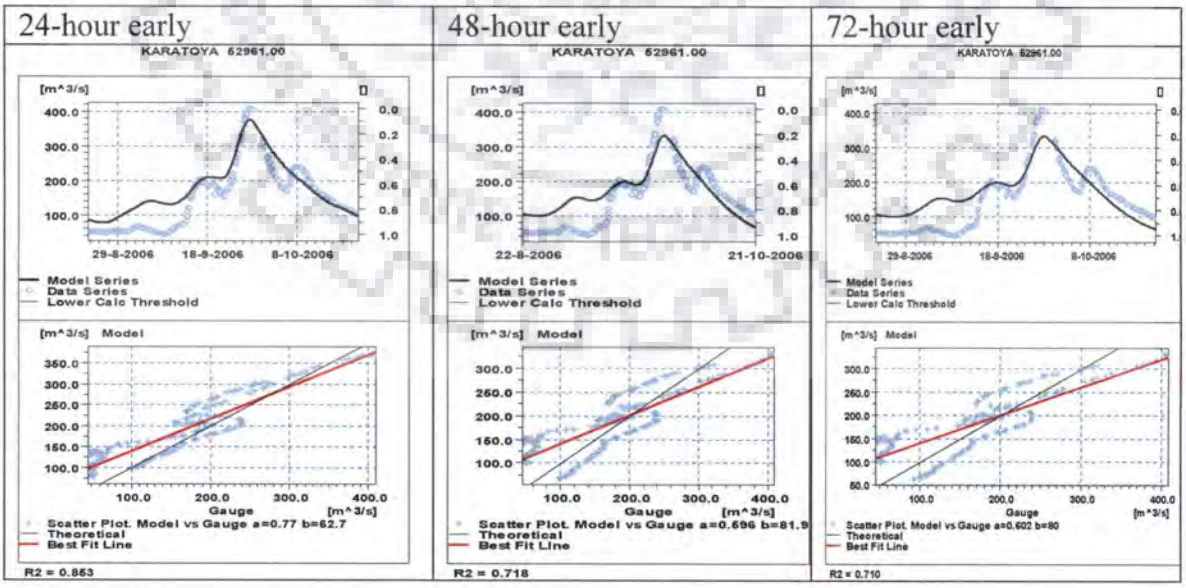


Figure 5.11: Time series and scatter plots of 24-, 48-, and 72-hour early forecasting by JFFS

Table 5.12: Quantitative difference of uncertainty among the 24-, 48-, and 72-hour early forecasted by JFFS

Descritption of model results	**24-hour early forecasting**	**48-hour early forecasting**	**72-hour early forecasting**
Efficiency index R^2	0.853	0.763	0.718
Correlation coeficient	0.924	0.875	0.843
Volume error, %	17.926	24.827	12.837
Peak error, %	-8.035	-6.023	-18.752
Peak time error, hour	-0.25	-0.5	-1
Slope, 'a'	0.77	0.653/0.7	0.602
Intersection 'b'	62.7	90.1	80

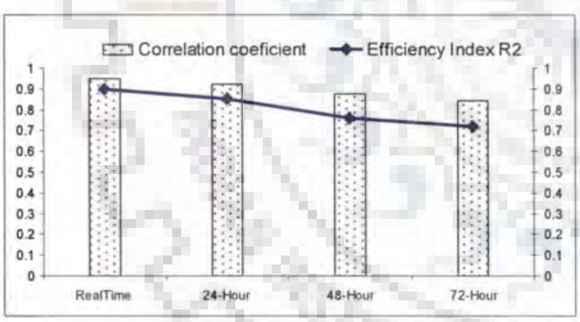


Figure 5.12: Graphical representation of Nash Sutcliffe's efficiency index and coefficient of correlation.

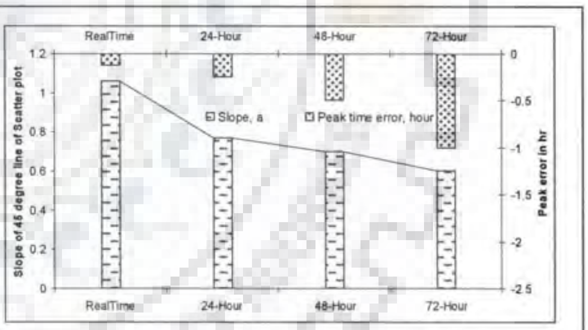


Figure 5.13: Graphical representation of peak time error and the slope of the 45^0 line of scatter plot

5.2.3 MIKE11-FF module

To obtain maximum accuracy of the real-time measurements in the forecasts, an automatic updating (data assimilation) routine MIKE11-FF (DHI, 2004) is included in MIKE11 NAM-HD. This updating routine matches the model result with the observed data prior to the Time of Forecast (ToF). The Figure 5.14 is the conceptual flowchart to define the simulation time period of the forecasting procedure. The Time of Forecast (ToF) is defined in relation to the

Hindcast and the Forecast Period. The Hindcast Period defines the simulation period up to ToF and is specified in the simulation file.

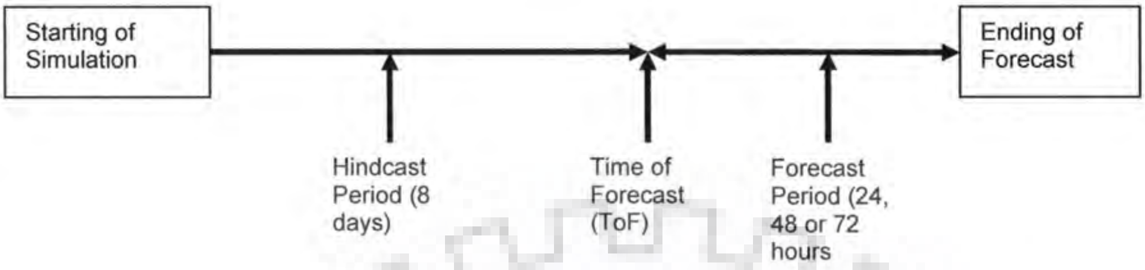


Figure 5.14: Conceptual flowchart of simulation period of forecasting procedure.

The accurate boundary and rainfall forecasts, well-calibrated model and the updating efficiency give accurate forecasting. The advantages of applying real-time updating to provide accurate flood forecasting is widely recognized (WMO, 1992). The MIKE11 FF is an automatic real-time updating routine, which is used to minimize two different types of deviations or errors between measured and simulated data, namely amplitude and phase error (Jorgensen and Host-Madsen, 1997). The updating procedure (Rungo et al., 1989) distinguishes between the two error types and makes corrections accordingly by minimizing the objective functions given below:

$$\sum_{i=1}^{n}(F_i(M_i-(S_i+A_e-(S_i-S_{i+1})/\Delta T\times P_e)))^2 \quad (5.18)$$

Where: A_e is amplitude error (m^3/sec); P_e is phase error (sec); M is measured discharge (m^3/sec); S is simulated discharge (m^3/sec); F is weighted factor; N is number of values included and Δt is time step (sec). The purpose of the calibration of the update parameters is to distinguish correctly between deviations in time (phase errors) and deviations in volume (amplitude errors). Refsgaard (1997) discussed the merits and disadvantages of different updating schemes. Jonch-Clausen and Refsgaard (1984), Refsgaard and Ghanekar (1986) and Refsgaard et al. (1988) recognized the importance of incorporating updating procedures for realtime forecasting.

5.2.3.1 Updating of JFFS model

The developed JFFS by using MIKE11 NAM and HD model has been updated with the observed water level/river stages at Badarganj of chainage 108.516 km of C.Jamuneswari

River. The measured and simulated water levels are compared and analyzed in the hindcast period and the simulations are corrected to minimize the discrepancies between the observations and model result. The Table 5.13 shows that the model hydrograph has some residual of error in the phase and peak after updating the model.

Table 5.13: Comparison of the results before and after updating by MIKE11-FF module

Hindcast Result	Before Updating	After Updating	Remarks
Efficiency index (R^2)	0.803	0.989	Model efficiency improved up to satisfaction
Correlation coeficient	0.896	0.998	Association of model result and observed data is improved
Volume error (%)	0.505	-0.005	Error minimized
Peak observed value, (m)	31.84	31.84	
Peak modelled value, (m)	32.661	31.89	Reduced towards observed 31.94 m
Peak error %	2.578	0.158	Peak has been more adjusted
Peak time error (hrs)	2.00	0.000	Phase error has been more adjusted

5.2.3.2 Updated forecast results

The updated model has been used to forecast water level at Badarganj upto 72 hours lead time. Simulation run, using 8 days hindcast period (before ToF), has been done for 24-, 48-, and 72-hour lead time or in advance forecasting and the comparative performance is also found in the Table 5.14

Table 5.14: Updated forecast result for 24-, 48-, and 72-hour lead-time

Updated Forecast Result	24 hours	48 hours	72 hours
Efficiency index R^2	0.920	0.870	0.840
Correlation coeficient	0.970	0.930	0.880
Scatter plot slope, a	1.010	1.110	1.230
Volume error in %	0.008	0.231	0.519
Peak error in %	0.087	0.507	-0.044
Peak time error, in hrs	0.000	0.000	0.000

5.3 Conclusions

In this Chapter, flood forecasting, JFFS has been developed by calibrating and validating MIKE11 NAM, HD, and FF Module. The MIKE11 NAM model has been calibrated for the years 2003 to 2005. The MIKE11 hydrodynamic model has been integrated with NAM model to improve the results by tuning Manning's coefficient.

The 24-, 48-, and 72-hour forecasted ECMWF rainfall data for 2006 have been used in the JFFS for flood forecasting in the Jamuneswari catchment area. The results show that with the increase of forecast lead-time, the accuracy decreases.

For increasing the accuracy of flood forecasting results, the JFFS has been updated using MIKE11 FF module with satisfactory results. The following suggestions are made for further improvement of JFFS.

- The existing network of hydrometerological stations should be scientifically designed to improve the results. The raingauges of key stations should be replaced by automatic raingauges for better results.
- In absence of evapotranspiration data, evaporation data of nearby stations have been used in the model. Use of actual evapotranspiration data shall improve the efficiency of JFFS.
- Old cross sections which were measured 12 years back have been used in the model. These cross sections need to be replaced by latest measurements for further improvements of the results.
- The studies initiated in this thesis should continue for Jamuneswari catchment in future and such studies should be taken for other basins.

Chapter 6 - Estimation of Design Flow and Stage using Frequency Analysis and MIKE11 Modeling

6.0 Introduction

Floods are one of the major causes of loss of life and physical property every year across the globe affecting adversely the overall economy of a country. Flood is a natural disaster, but its behavior changes due to human intervention in the flood plains and catchments such as construction of houses, roads, and bridges, consequently increasing the risk and losses to the properties and life (Hassan et al., 2006). There are two common approaches to manage a flood problem viz., (1) structural measures and (2) non-structural measures and in both cases of flood management, design flow and stage have vital roles.

The design flow and stage are important events to design different hydraulic structures of a flood management project. The design flood stage is also useful to prepare flood extent maps to assess vulnerbility to flood damage for different return periods. The objective of this case study is to determine design flood flows and corresponding flood stages for different return periods using frequency analysis and MIKE11 modeling respectively, at the location where observed data are scarce or expensive to collect. MIKE11 is a physically based deterministic hydrodynamic model to generate the discharge, stage, and their relation in a river network. Rating curve is a conventional practice to compute the corresponding river stage or discharge. Generally, rating curves are developed from observed discharge and stage data. In case of data scarcity, the discharges and stages can also be routed by mathematical modeling at any point of interest within the model domain.

A comprehensive study was conducted in Teesta River subcatchment under Brahmaputra basin in Bangladesh to determine the flood flow and stage for different return periods. Rainfall-runoff (NAM: Nedbor-Afstromnings-Model) module integrated with Hydrodynamic (HD) module of MIKE11 mathematical model was applied in this study for routing river stage and discharge. Finally, a rating curve (Q-h relation) equation was developed using the model output.

Flood frequency analysis was carried out by checking the suitability of different distributions using discharge data to determine the flood magnitude for different return periods. The designed discharges were then used to find the river stage from the developed equation of Q-h relationship.

6.1 Description of study area and data used

The study area is located in Teesta subcatchment of Bangladesh. The Teesta River originates from the Himalayas in Sikkim state of India. It flows approximately 180 km through a mountainous area before entering into the alluvial plains of Northwestern part of Bangladesh. It keeps flowing in a braided course for a length of 96 km before crossing the India-Bangladesh border. After traveling 121 km, it joins the Jamuna River near Chilmari in Bangladesh. The location of the study area has been shown in the Figure 2.3 under Chapter 2. The Dharla river is also flashy in nature, it enters into Bangladesh at Talukshimulbari from India, and confluences with Jamuna at Gujimari.

The Brahmaputra (total length 2,700 km) originates from Chemayung-Dung glacier near Manassarowar and Mount Kailas. In Bangladesh, the river is named as Brahmaputra upto Bahdurabad (71 km) and from Bahdarubad to Aricha it is named as Jamuna (205 km). The Brahmaputra-Jamuna is one of the largest river in the world which flows through Tibet, China, India, and Bangladesh. The earthquake and catastrophic flood in 1787 changed the main course of Brahmaputra near Bahadurabad and it now passes southwards through Serajganj District to the confluence with the Ganges at Aricha. The original Brahmaputra, flowed toward southeast passes through Jamalpur, Mymensingh, and Kishorgonj districts to confluence with the Upper-Meghna near Bhairabbazar and is now known as "Old-Brahmaputra". The main course of the Brahmaputra is now known as river Jamuna, it carries an average discharge of 4,000 m^3/sec water in the monsoon and it experienced maximum discharge of 98,600 m^3/sec in August 1998. Ghagot is a short length river, originating inside Bangladesh and confluences with Jamuna. The adjoining river systems bypass excess flow into Jamuna through this river.

The area of Teesta subcatchment in Bangladesh is about 2,000 km^2. The riverbed is comprised of fine to medium sand common to an alluvial floodplain. This area is classified as shallow depressions and valleys of moribund river channels, formed by long morphological history of changes in the river courses. The general slope of the river varies from 0.47 to 0.55 m/km. The Teesta subcatchment is vulnerable to flooding in each year. There are two main tributaries of the river Teesta namely, Naotara and Buri-Teesta. Flash floods are caused by the Teesta River, and if the peaks are observed in rivers Jamuna and Teesta simultaneously, the worst flood situation occurs in the area. In this study, only Bangladesh portion of the Teesta subcatchment has been considered for analysis.

The region has an average annual rainfall around 1900 mm. Maximum temperature ranges from 25°C in January to 35°C in April/May. Evapotranspiration reaches to a maximum in April when temperature, sunshine, and wind are all close to their maxima (ODA and JICA, 1993).

The hydrometeorological data were obtained from Flood Forecasting and Warning Centre (FFWC), which is part of the Bangladesh Water Development Board (BWDB). The collected *Rainfall data* (1991 - 2004) of 10 stations, i.e., Dewangonj, Jamalpur, Mymensingh, Chilmari, Gaibandha, Dalia, Panchagar, Rangpur, Kaunia, and Kurigram were used for MIKE11 NAM model setup. Due to unavailability of *evaporation* data, yearly average value of 1,460 mm was taken for MIKE11 NAM model setup. *Discharge data* (1991 - 2004) at Dalia on River Teesta and *River Stage data* (1991 - 2004) at Kurigram on river Dharla, at Gaibandha on river Ghagot and at Noonkhaowa and Bahdurabad on river Jamuna were used for boundary of MIKE11 HD Model setup. *River cross sections* of seven rivers, e.g., Teesta (chainage from km 13.50 to 121.00), BuriTeesta (chainage from km 0 to 35.00), Naotara (chainage from km 0 to 10.00), and Ghagot (chainage from km 132.00 to 136.00). Dharla (chainage from km 21.50 to 48.00), Jamuna (chainage from km 8.00 to 84.500) and Old Brahmaputra (chainage from km 0 to 31.00), measured in 1999, were used for MIKE11 HD model setup. The stream network was delineated using ArcGIS9.3. *Shuttle Radar Topography Mission (SRTM) 90m digital elevation model (DEM)* (Version-4) available in public domain (http://srtm.csi.cgiar.org/). *River stage data at* Chilmari on River Jamuna available for the period from May 1, 1996 to December 31, 2003 were used for comparing the simulated result.

6.2 Flood frequency analysis

The procedure for estimating the frequency of occurrence (return period) of a hydrological event such as flood is known as frequency analysis (Kwaku and Duke, 2007). The frequency analysis begins with the calculation of the statistical parameters required for a proposed probability distribution from the given data (Chow et al., 1988). In this study, annual flood series of maximum discharges at Kaunia station of 22 years, obtained from FFWC, were used for designing 25-, 50-, and 100-year flood flow. Several tests for checking the consistency and quality of data were carried out. The data were also checked for outliers, which are data points that depart significantly from the trend of the remaining data (Chow et al., 1988). According to procedure given by Chow et al. (1988), the computed threshold values for high outliers and low outliers are 12,566 and 1,419 respectively, which are within corresponding observed upper and lower threshold values 8,577 and 1,684, respectively. This result shows that the given time series can be used for flood frequency analysis.

Statistical parameters, i.e., mean, standard deviation, coefficient of skewness, and coefficient of kurtosis for original series, are 4627, 1948, 0.33, and -1.04, respectively and for log-transformed series are 8.34, 0.45, -0.26, and 14.83 respectively.

The hydrologic data must be free from short-term dependence as well as long term-dependence and must be stationary. *Turning point (TP) test (i.e., Kendall's test) for randomness* is a nonparametric test carried out for testing short-term dependence in a time series (Lye and Lin, 1993). *Anderson's correlogram (AC) test* checks the randomness of the annual flood series. *Rank difference test* (Meacham, 1968), as referred by Lye and Lin (1993), also test the randomness. *Kendall's rank correlation test* checks the stationarity of a series (Shrestha, 2000). Since there is no rising or falling trend in this series, so linear regression test (Kottegoda, 1980) was not applied. The Mann–Kendall test was also used in this study. According to Yue et al. (2002) the lag-one ($k = 1$) autocorrelation coefficient, $r_1 = -0.371$, was computed and since $\frac{-1-1.645\sqrt{n-2}}{n-2} \leq r_1 \leq \frac{-1+1.645\sqrt{n-2}}{n-2}$ i.e., $-0.41 \leq -0.37 \leq +0.311$, which indicates the data are independent at 10% significant level for which no prewhitening is required. Here, n is the length of the data series.

$Z_{cal's}$ of Turning point, Anderson's correlogram, Rank difference, Kendall's rank correlation and Mann Kendall test (Kendal, 1975 and Mann, 1945) are given in Table 6.1 which confirm that the annual flood series is free from short term dependence.

Table 6.1: Summary of randomness and stationary test result

Test	Z_{cal}	$Z_{critical}$ α (%)			Remarks
		1	5	10	
Turning Point	0.35	2.58	1.96	1.65	Random
Anderson's Correlogram	1.43	2.58	1.96	1.65	Random
Rank Difference	1.43	2.58	1.96	1.65	Random
Kendall's Rank Correlation	1.27	2.58	1.96	1.65	Random
Mann Kendall Test	1.18	2.58	1.96	1.65	Random

Z_{cal} is calculated standard normal deviate, α in percent is the level of significance in percent and $Z_{critical}$ is the standard normal deviate (standard normal distribution, with mean $\mu = 0$ and standard deviation $\sigma = 1$) for α percent significant level.

The *Hurst coefficient* (Hurst, 1951) is at present the only measurement available for testing long-term dependence (Lye and Lin, 1993). Haan et al. (1982) suggested that the range of the cumulative departures depends on the length of the period. *Hurst's coefficient* was also computed for checking the long-term dependence in the data recorded at the Kaunia station. The computed value of Hurst's coefficient, K, is 0.47 which is less than all the critical values. It implies that the annual flood series is also free from long-term dependence. The analysis of short-term dependence and long-term dependence show that the obtained time series is random in nature and hence can be used for flood frequency analysis.

Log-normal (LN), Pearson type-III (PT-III), log-Pearson type-III (LPT-III), and Gumbel or Extreme Value Type-I (EV1) distributions were used to estimate floods for 25-, 50-, and 100 year return periods. There are number of plotting position formulas developed by different investigators but Weibull's plotting-position formula is the most acceptable and widely used in hydrology. Chow et al. (1988), Haan et al. (1982), Singh (1994), McCuen (1985), Subramanya (1996), Gray (1973), Gupta (1989), and Bedient and Huber (2002) recommended the use the Weibull's plotting position formula. Thus, in the present study, Weilbull's plotting position formula has been used. Estimation of different return period floods, by different probabilty distributions, have been presented in Table 6.2.

Table 6.2: Summary of design floods for 25-, 50-, and 100-year return periods based on different distribtutions.

Return Period, T -Year	LN Distribution	PT-III Distribution	LPT-III Distribution	EV1(Gumbel) Distribution
25	9258	8247	8890	8611
50	10607	8961	9964	9679
100	11988	9621	11011	10740

A number of analytical tests (Vogel et al., 2009) such as the chi-square test, Kolmogorov-Smirnov (K-S) test (Kolmogorov, 1975), D-index test, and L-moment diagram ratio have been conducted for testing the goodness of fit of the proposed distribution (Appendix 6.1). The results of chi-square, Kolmogorov-Smirnov and D-index goodness of fit tests show that EV1 (Gumbel) distribution fits well based on chi-square test. All distributions are well fitted by KS test. On the other hand, Pearson type – III distribution fits well based on D-index statistics. In order to find the best fit distribution as described by Rao and Hamed (2000), *L-moment diagram and ratio tests* (Kumar et al., 2000 and 2003) were conducted. L-moment is less biased than traditional product moment estimates (Hosking, 1990, Hosking and Wallis, 1993, 1997 and Wallis, 1988). The goodness of fit is judged by the difference between regional L-kurtosis values and the theoretical L-kurtosis values. Ratio of L-kurtosis (0.1454) and L-skewness (0.2301) have fallen on the curve of Pearson type-III.

The Pearson type-III distribution is found to be the best fit distribution. Hence, the flood flow computed from PT III distribution was considered as the design flood.

6.3 Modelling using MIKE11 software

MIKE11 is a dynamic modeling tool for rivers and channels with a graphical user interface, MIKE Zero. MIKE Zero is windows based software integrated with the computational core of MIKE11, which includes graphical editing facilities and improved computational speed. Geometric inputs like river network, river cross sections, etc are imported from GIS environment to MIKE11 environment.

MIKE11 contains the modules Hydrodynamic (HD), Advection-Dispersion (AD), Sediment Transport (ST), ECO Lab (Including Water Quality modeling etc.), Rainfall-Runoff (RR), Flood Forecasting (FF), Data assimilation (DA) and Ice modeling (DHI, 2004). In this study, rainfall-runoff (RR) and hydrodynamic (HD) modules were used to compute the design flood flow and stage at different locations on the Teesta River. The MIKE11 was used because of its availability for this case study. From the early 1990's MIKE11 NAM and HD model is being used in Bangladesh for flood forecasting in the complex nature of the river system (Paudyal, 2002). The operation process of MIKE11 NAM and HD model simulation is shown in Figure 6.1. In the subsequent sections, brief description of MIKE11 NAM and HD, application of MIKE11, the procedures for model setup, comparison of model result with observed value, and development of rating curve are presented.

Among the different types of Rainfall-Runoff model specified in MIKE11, the NAM method was selected for this study. This NAM model was originally developed by Nielsen and Hansen (1973). NAM simulates four different and mutually interrelated storages that represent different physical elements of the catchment. These storages are snow storage, surface storage, lower or root zone storage, and groundwater storage. In this study, snow storage has not been considered. NAM produces runoff based on evapotranspiration, soil moisture content, groundwater recharge, and groundwater level data. The detailed description of the model is described by Nielsen and Hansen (1973) and also documented by Danish Hydraulic Institute (2004).

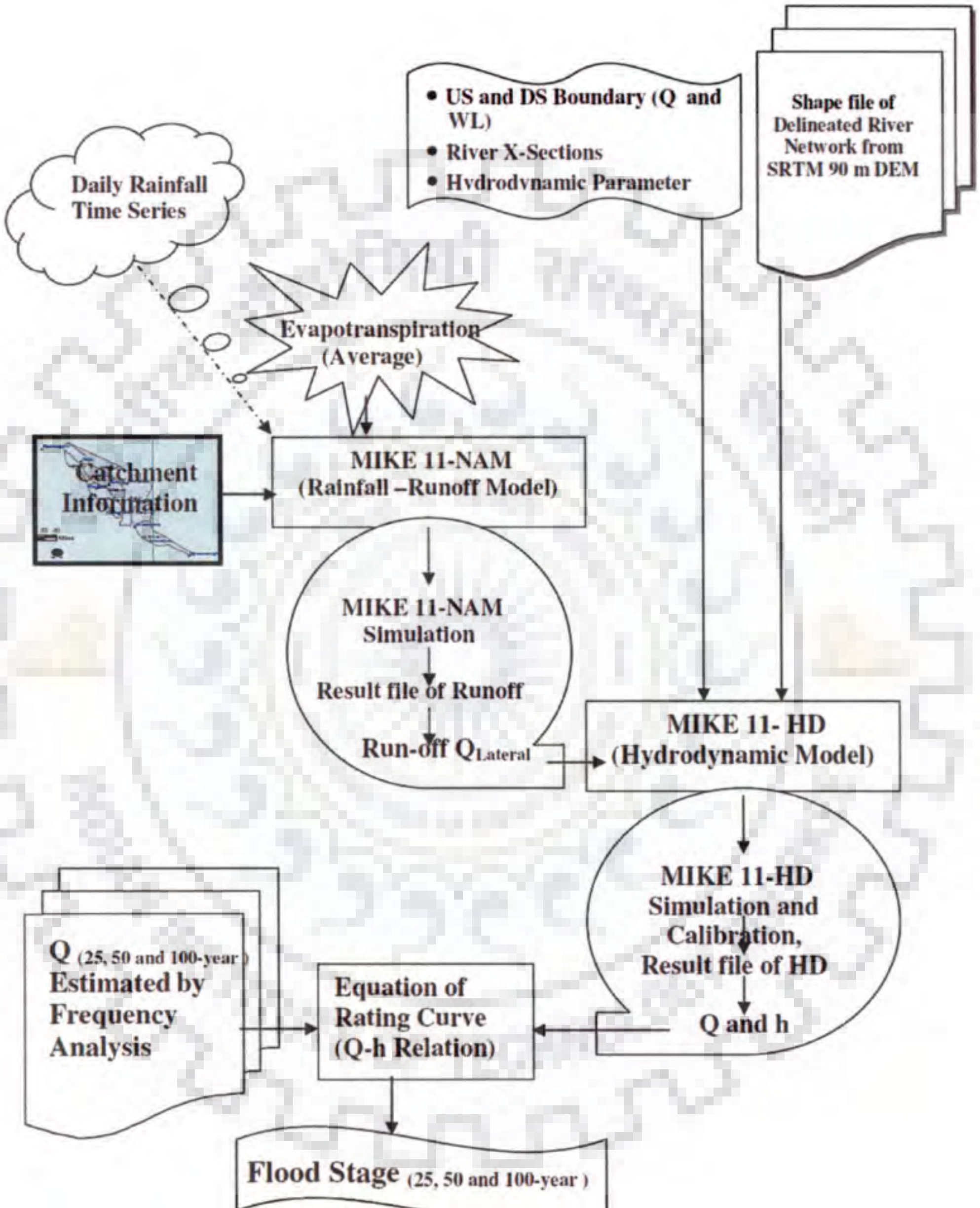


Figure 6.1: Flow diagram of MIKE11 NAM and HD models simulation for preparing rating curve

MIKE11 hydrodynamic (HD) module solves the Saint-Venant's equation with an implicit finite difference method developed by Abbott and Ionescu (1967) for the computation of flows in rivers. It can model subcritical as well as supercritical flow conditions. MIKE11 HD applied with the dynamic wave description solves the vertically integrated equations of conservation of continuity and momentum, based on the following assumptions (DHI, 2004):

- The flow is one-dimensional; depth and velocity vary only in the longitudinal direction of the channel. This implies that the velocity is constant and the water surface is horizontal across any section perpendicular to the longitudinal axis.

- Water is incompressible and homogeneous; i.e., there is negligible variation in density.

- The bottom slope (of the channel) is small; thus the cosine of the angle with the horizontal may be taken as 1.

- The wavelengths are large compared to the water depth. This ensures that the flow everywhere can be regarded as having a direction parallel to the bottom. That is vertical accelerations can be neglected and a hydrostatic pressure variation along the vertical can be assumed.

- The flow is subcritical (supercritical flow may also be modeled in MIKE 11 with more restrictive conditions).

The formulation can be applied to branched and looped networks and quasi-two-dimensional flow simulation on floodplains (Paudyal, 2002). Based on NAM-calculated lateral inflow and additional inflow from external boundaries, the hydrodynamic (HD) module predicts water levels and reservoir inflows. The conservation of mass and momentum equations were modified for varying width and water levels. These equations can simulate flow through cross-sections of any shape when divided up into a series of rectangular cross sections (DHI, 2004). The hydraulic resistance is based on the friction slope from the empirical equation, Manning or Chezy, with several ways of modifying the roughness to account for variations throughout the cross-sectional area. Chowdhury (2000) described the basic concept of MIKE11 NAM and HD model briefly.

Markar et al. (2004) evaluated Info-Works, HEC-RAS (Hydrologic Engineering Centers River Analysis System), and MIKE11 hydrodynamic model to assess the suitability for integration into the flood forecasting system (FFS) with criteria of accuracy, technical capability and ability to interface with customized FFS. They mentioned that the model run times for MIKE11 were much smaller and the stability of MIKE11 runs was less sensitive to specified initial conditions. Markar et al. (2004) then found that MIKE11 is more suited for using in FFS of Yangtze river in China.

MIKE11 has also been used to simulate flow in large river systems. Paudyal (2002) applied MIKE11 NAM and HD model for simulation of complex river system in Bangladesh to develop flood forecasting and warning system. He mentioned that use of MIKE11 NAM and HD has been found to be very promising in building the flood-preparedness system. Patro et al. (2009) calibrated the one dimensional model MIKE11 using river water level and discharge data of various gauging sites for the monsoon period in the delta region of Mahanadi River basin in India. They found that the calibration and validation results of MIKE11 show that the model performs quite satisfactorily in simulating the river flow for the delta region of Mahanadi river basin.

Ruch et al. (2008) developed ccontinuous flood forecasting combined with automatic forecast correction in the Mur River using the flexible software solution by the rainfall runoff model NAM, and the hydrodynamic model MIKE11, and the Flood Forecasting shell MIKE FLOOD WATCH easily allows to extend the entire system to other tasks by adding specific MIKE11 modules.

6.3.1 NAM model setup

The catchment is divided into eight subcatchments having different areas. Due to non-availability of evapotranspiration data in each subcatchment, yearly average data has been considered for the Teesta River subcatchment. The time series of "daily" rainfall for ten stations from 1990 to 2004 have been used as rainfall input to NAM model. The basic parameters specific to NAM Model along with their short description are given by DHI (2004).

The calibration process starts with the water balance. The water balance should be formulated by total evapotranspiration equal to net precipitation minus runoff. The evapotranspiration will increase when increasing the maximum surface storage (U_{max}) and root zone storage (L_{max}). The peak volume is adjusted by changing the overland flow runoff coefficient (CQOF) and the shape of the peak depends on the time constant used in the runoff routing (CK_{12}). The parameters U_{max}, L_{max}, CQOF and CK_{12} were adjusted by different values for eight subcatchments.

Decrease in overland flow or interflow results in higher base flow. The shape of the base flow recession is a function of the base flow time constant (CKBF). The root zone threshold value of overland flow (TOF), threshold value of interflow (TIF), and threshold value of ground water recharge (TG) are considered to be zero in the beginning of the calibration. These threshold values are adjusted by heuristic approach. Accordingly, the parameters used in the model were adjusted for eight subcatchments.

6.3.2 HD model setup

River network

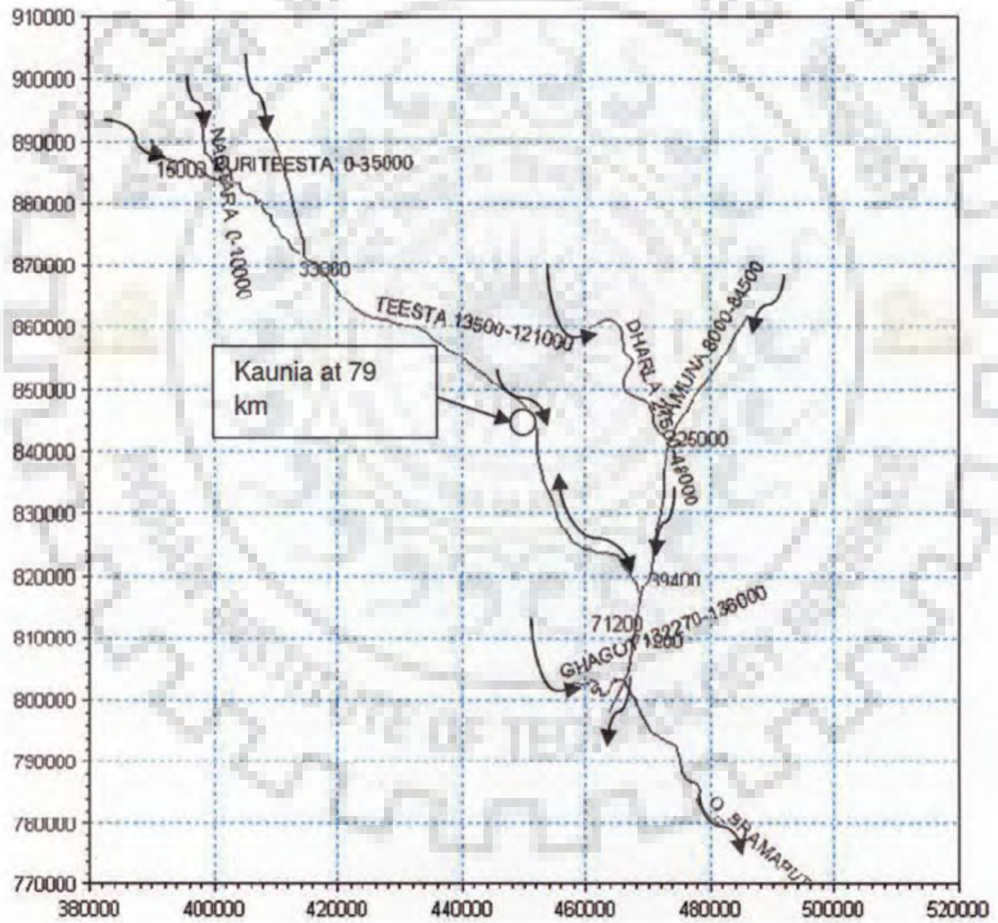


Figure 6.2: River network used in HD model

To setup the HD Model, the river network of the rivers Buri-Teesta (00 to 35.00 km), Naotara (00 to 10.00 km), Teesta (13.50 to 121.00 km), Dharala (21.5 to 48.00 km), Ghagot (132.27 to 138.00 km), Jamuna (8.00 to 84.50 km) and Brahmmaputra (00 to 31.00 km) have been considered. Figure 6.2 shows the river network of the model and their connectivity. The model network lies within the Bangladesh territory. Stage in river Teesta is also influenced during flood period by other rivers that have also been considered in the river network. For the modeling purpose, flow direction is taken positive, maximum distance between two adjacent points (dx) is taken 1000 m, and the river type is taken as regular.

River cross sections

The cross sections as taken in the year of 1998 by Bangladesh Water Development Board have been used in this study. A sample cross section at Kaunia on Teesta river is shown in the Figure 6.3. The longitudinal profiles of the river Teesta, Jamuna, and Brahmaputra also given in Figure 6.4.

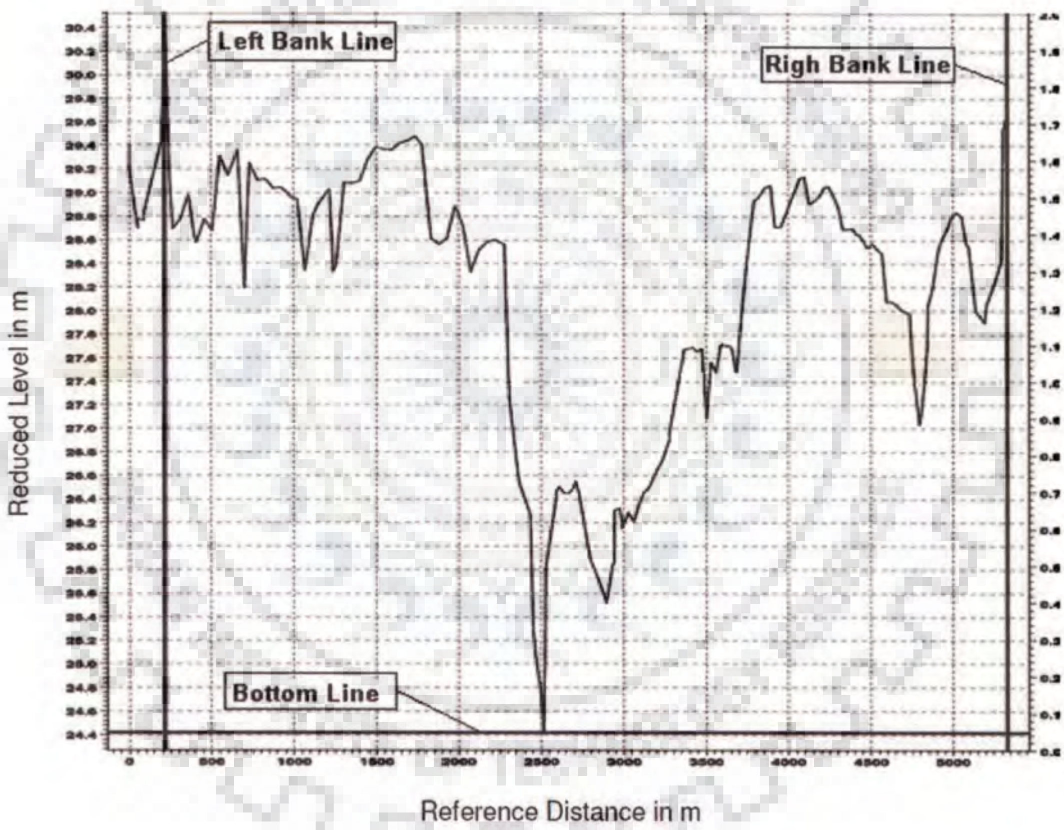
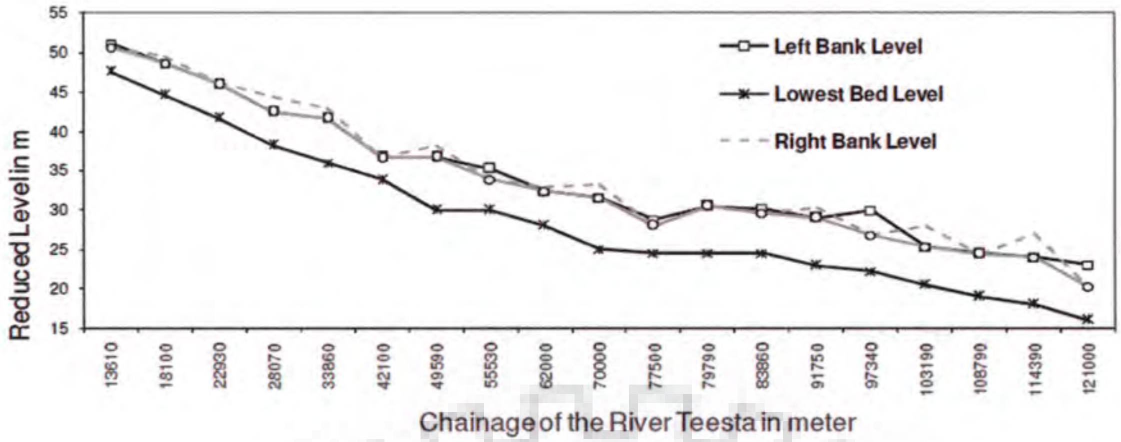
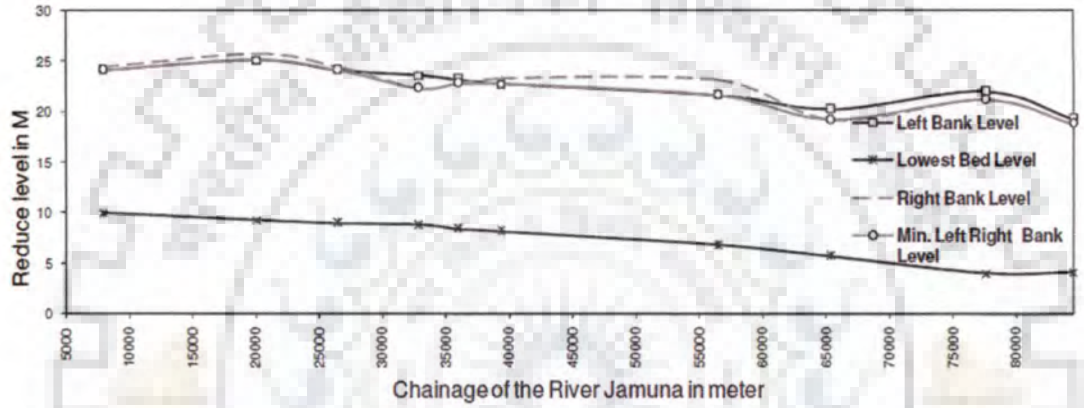


Figure 6.3: Representative cross section of the River Teesta at Kaunia chainage 79.79 km

Boundary conditions

The selection of boundary conditions depends on the availability of data and the physical situation of the model area. Boundary conditions could be *constant discharge* from a reservoir; a *discharge hydrograph* of a specific event; *constant water level* e.g., in a large receiving water body; *time series of water level;* e.g., tidal cycle, and a reliable *rating curve*, e.g., from a gauging station.





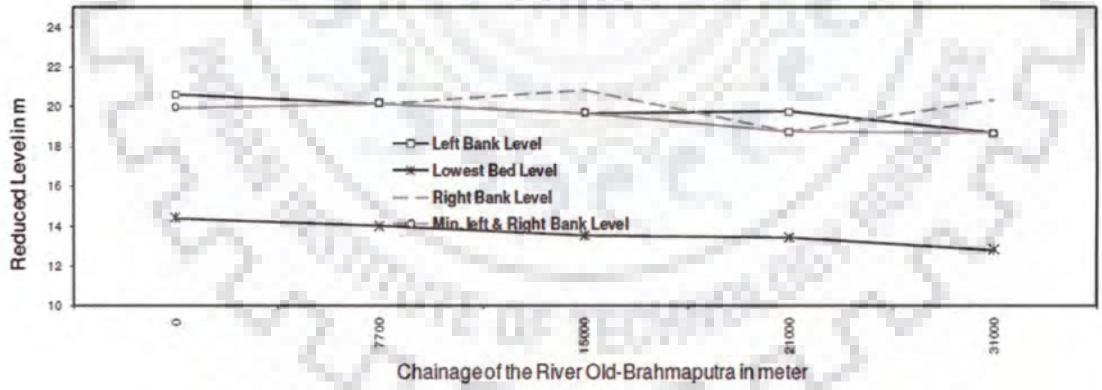


Figure 6.4: Longitudinal Profile of River Teesta (Chainage 13610 m to 121000 m), Jamuna (Chainage 8000m to 84500 m) and Old-Brahmaputra (Chainage 0 m to 31000 m)

The *upstream boundary conditions* of river Jamuna, Dharla, and Ghagot are defined as the water levels measured by BWDB on three hourly basis at Noonkhaoa, Kurigram, and Gaibandha stations. The upstream boundary condition of the Teesta River is the inflow time series observed by BWDB. Since Naotara and Buri-Teesta rivers originate within the study area, inflows in the upstream of these rivers are not significant. Hence, the boundary conditions of rivers Naotara and Buri-Teesta are arbitrarily taken as constant inflow, i.e., 1 m^3/sec.

The *downstream boundary condition* of the Jamuna River has been taken as the water level collected at Bahadurabad. On the other hand, the length of the river Old-Brahmaputra has been considered as 31 km down the confluence. Due to nonavailability of a gauging station, Q-h relationship (i.e., rating curve) developed by BWDB for flood forecasting in Bangladesh was given as downstream boundary condition.

Hydrodynamic (HD) parameter

The Teesta river is the tributary of the Jamuna river and Jamuna carries the total discharge of Brahmaputra basin to pass toward the Bay of Bengal. During peak discharge in the Jamuna, Teesta gets some backwater effect when flash flood occurs in Teesta catchment. The tributaries of Teesta, Naotara, and Buriteesta are also flashy in nature. Dharla is also a flashy river and gets some backwater effect from Jamuna; i.e., the whole water body of the river network system of the study area changes over time and space. On the other hand, the average bed slope of the river Teesta is 1:3,500, Naotara is 1:18,000, Buri-Teesta is 1: 20,000, Dharla is 1:5,500, Jamuna is 1:14,500, and Old-Brahmaputra is 1: 40,000. The slope data indicate that the study area is very flat. Hence, high order fully dynamic wave approximation has been considered to simulate the above river system. The global initial condition has been taken as 2 m water depth.

6.3.3 Integration of rainfall-runoff (NAM) model with HD model

NAM Model has then been integrated with HD model to input the lateral inflow from eight subcatchments to the river channels. The reach lengths of seven rivers were connected with eight subcatchments allocating the area to be drained with those reach lengths.

6.3.3 Simulation

Simulation period has been selected from 31 May 1996 to 30 November 2003 according to data length and their consistency. For HD model, fixed time step of 30 minutes and the result of NAM model have been selected as hot start of initial condition of hydrodynamic simulation. The computation of NAM and HD model give the time series of water level and discharge at each 1,000 m point with 30 minutes interval. The discharge and water level time series are generated at every alternate point. At the point of discharge generation a rating curve or discharge-stage (Q-h) relation can be obtained. The model generated inflow (Jamuna at 36,100 m, Teesta at 81,100 m, and Ghagot at 134,135 m) and outflow (Old-Brahmaputra at 26,000 m and Jamuna at 25,800 m) are shown in the Figure 6.5 (full simulation period) and Figure 6.6 (representative 1 year).

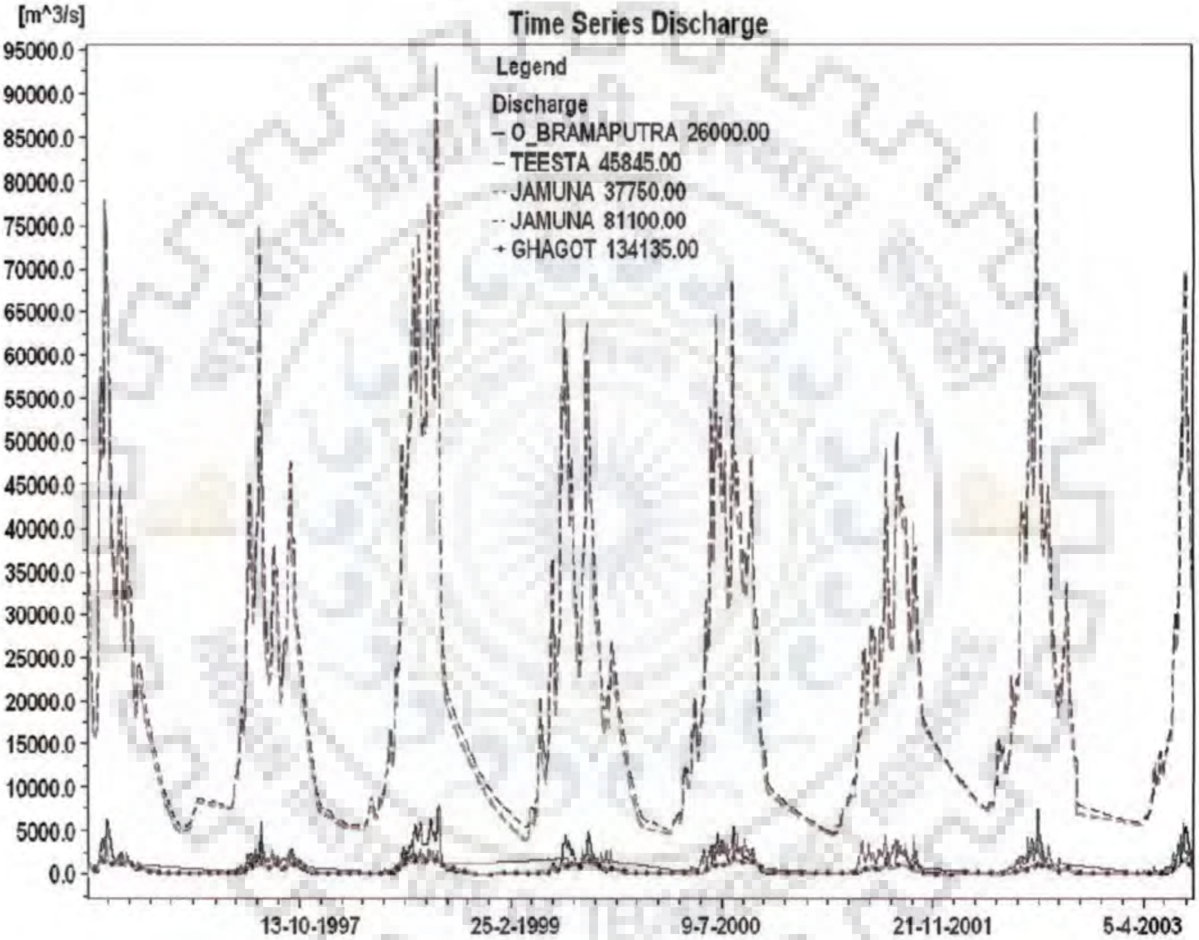


Figure 6.5: Model generated inflow (Jamuna at 37,750m, Teesta at 45,845m, and Ghagot at 134,135m) and outflow (Old-Brahmaputra at 26,000m and Jamuna at 81,100m) from May 1996 to November 2003.

6.3.4 Comparison of river stages and discharge

The calibration process uses graphical and numerical performance measures. The graphical evaluation includes comparison of the simulated and observed hydrograph and discharge. Though there were several studies available for performance evaluation of model, such as by

Aitken (1973) and Fleming (1975), the method given by Nash and Sutcliffe (1970) is widely used in the area of hydrology and water resources for the detection of systematic errors with respect to long-term simulation.

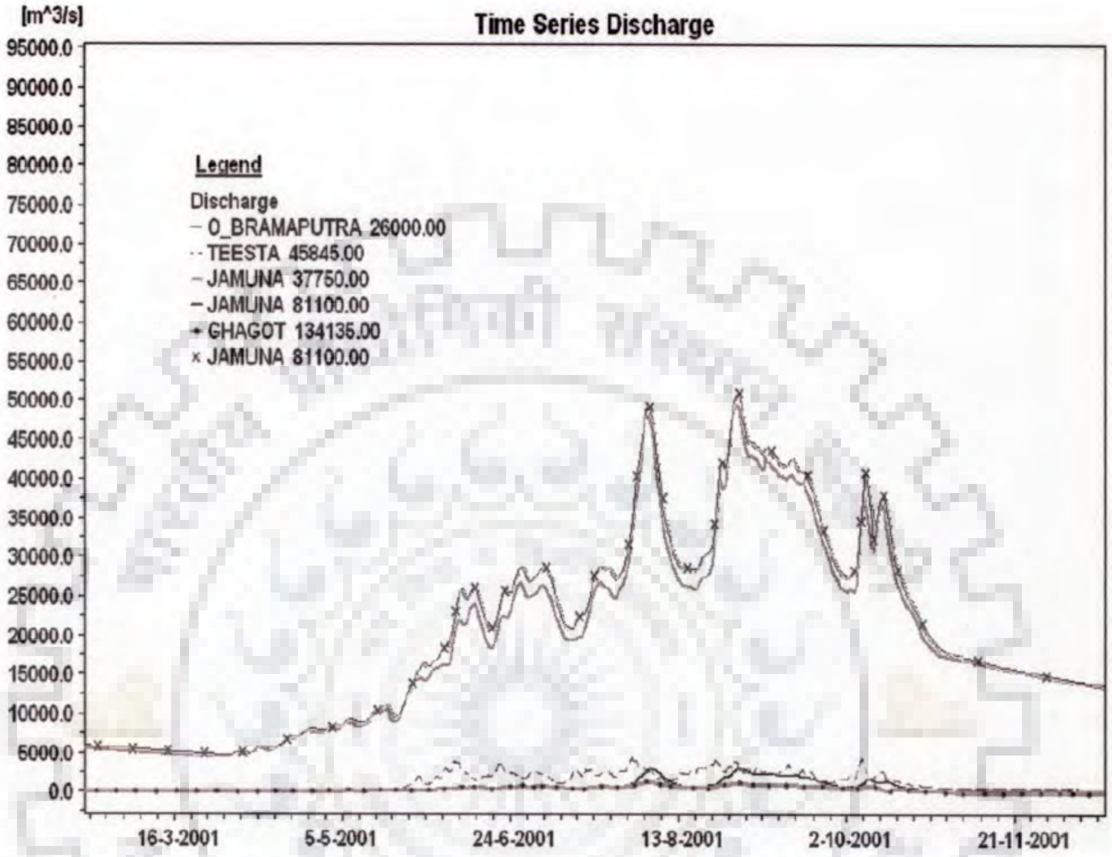


Figure 6.6: Model generated inflow (Jamuna at 37,750 m, Teesta at 45,845 m, and Ghagot at 134,135 m) and outflow (Old-Brahmaputra at 26,000 m and Jamuna at 81,100 m) for 2001.

The reliability of the MIKE11 NAM and HD was evaluated based Nash and Sutcliffe efficiency index (EI). The EI is given in equation (6.1).

$$EI = \frac{\sum_{i=1}^{n}(q_i - \bar{q})^2 - \sum_{i=1}^{n}(q_i - q_s)^2}{\sum_{i=1}^{n}(q_i - \bar{q})^2} \qquad (6.1)$$

Where q_i = Observed flow at time i number of data points

$\bar{q}$ = Mean value of observed flow

$= \frac{1}{n}\sum_{i=1}^{n} q_i$

q_s = Simulated flow at time i

n = Number of data points

A perfect match, corresponding to EI = 1, is not expected because of different error sources, including:

- Errors in meteorological input data,
- Errors in recorded observations,
- Errors and simplifications (assumptions) inherent in the model structure, and
- Errors due to the use of nonoptimal parameter values.

The resultant time series of river stages at Chilmari (Chainage 36,100 meter of the river Jamuna) has been validated visually comparing with the observed stage data from 31 May 1996 to 30 November 2003.

The model efficiency can be high for cases where there is a constant bias in the model result; that is, the model result is equal to the observation plus or minus a constant value. The better statistical parameters are the bias and mean absolute error or relative mean absolute error (Lettenmaier and Wood, 1993). Mean absolute error or relative mean square error is preferred to mean squared error because mean squared error or root mean squared error is influenced by the square of small numbers of large errors (Lettenmaier and Wood, 1993).

Statistical analysis was also carried out for obtaining parameters like relative bias, mean absolute error (MAE), relative MAE, efficiency index, and coefficient of correlation for the comparison of the results, and the equations of relative bias, mean absolute error (MAE) and relative MAE are given below where q_s is simulated value and q_i is observed values:

Relative Bias $= \dfrac{\frac{1}{n}\sum_{i=1}^{N}(q_s - q_i)}{\frac{1}{N}\sum_{i=1}^{N} q_i}$ (6.2)

Mean Absolute Error (MAE) $= \frac{1}{N}\sum_{i=1}^{N}|q_s - q_i|$ (6.3)

Relative Mean Absolute Error (RMAE) $= \dfrac{MAE}{\frac{1}{N}\sum_{i=1}^{N} q_i}$ (6.4)

The yearwise values of the statistical parameters are given in Table 6.3. The relative bias is the measures of the degree to which the model results are consistently above or below the observed value (Lettenmaier and Wood, 1993). Analyses of these parameters (Table 6.3) show the existence of systematic errors that spread over many years. It is also evident from the graph as shown in Figure 6.7.

Table 6.3: Statistical parameter for comparison of model results for through out the full year

SN	Statistical Parameters	Expected Values	Obtained from Observed and Result Values for each year								Averaged
			1996	1997	1998	1999	2000	2001	2002	2003	
1	Relative Bias	0.00	0.02	0.04	0.03	0.05	0.02	0.02	0.03	0.02	0.03
2	MAE	0.00	0.47	0.73	0.69	0.93	0.60	0.64	0.87	0.72	0.71
3	RMAE	0.00	0.02	0.04	0.03	0.05	0.03	0.03	0.04	0.04	0.04
4	EI	1.00	0.89	0.79	0.88	0.76	0.92	0.84	0.71	0.74	0.82
5	Correlation Coefficient	1.00	0.97	0.97	0.97	0.97	0.98	0.96	0.90	0.88	0.95

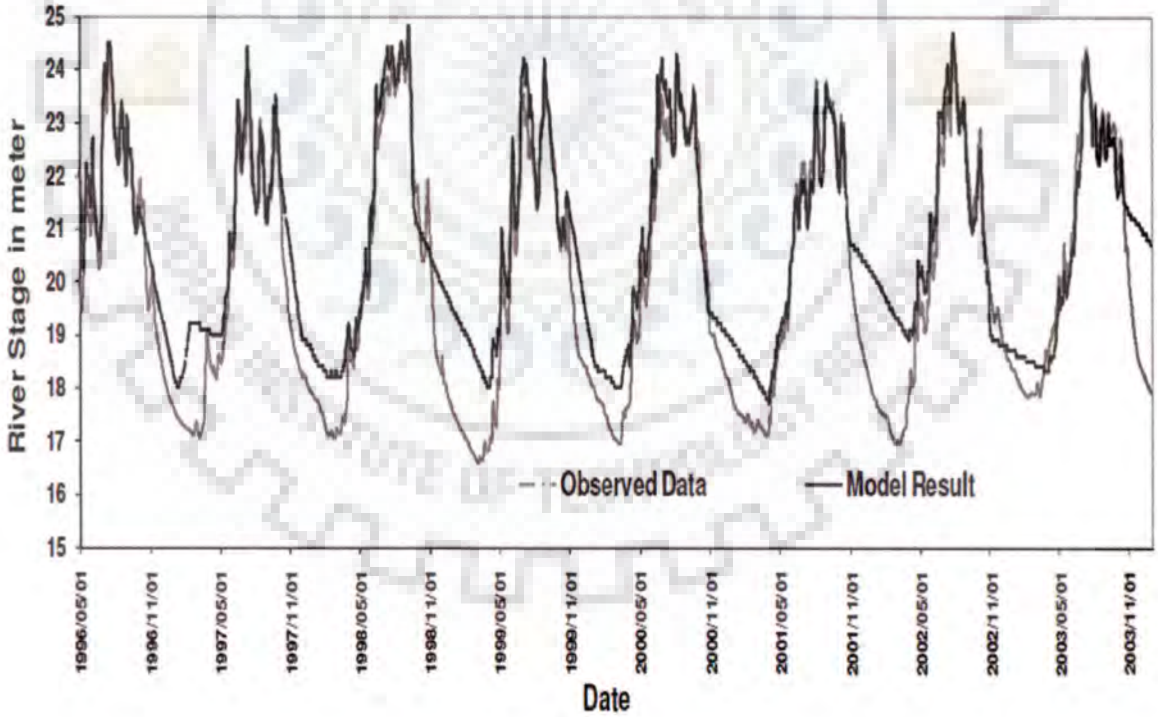


Figure 6.7: Graphical comparison of model results with the observed river stage at Chilmari (chainage 36,100 meter on river Jamuna) from May 1996 to November 2003.

It is clear that the model results are consistently above the observed value in the lean period only. It implies that either the quality of observed data in the lean period is not good or the model setup parameters require further adjustment for the dry period simulation.

Most of the floods in Bangladesh occur during the monsoon season. Hence, if we consider only monsoon period for the calibration and validation then a XY plot of the model result and observed value with a 45° line is shown in Figure 6.8. After considering the model result for monsoon period only, the error indices have been re-calculated and presented in Table 6.4. The average values of statistical parameters for either case were then compared with the expected value of these parameters. The statistical parameters for monsoon period are showing better results than the statistical parameters for full year.

The relative bias of the monsoon period indicate that the variability of model results and the observed data are minimized significantly. Efficiency index and coefficient of correlation show the same in both the cases. Table 6.4 shows that relative bias, mean absolute error, root mean absolute error, efficiency index and coefficient of corelation are good fit with the expected value.

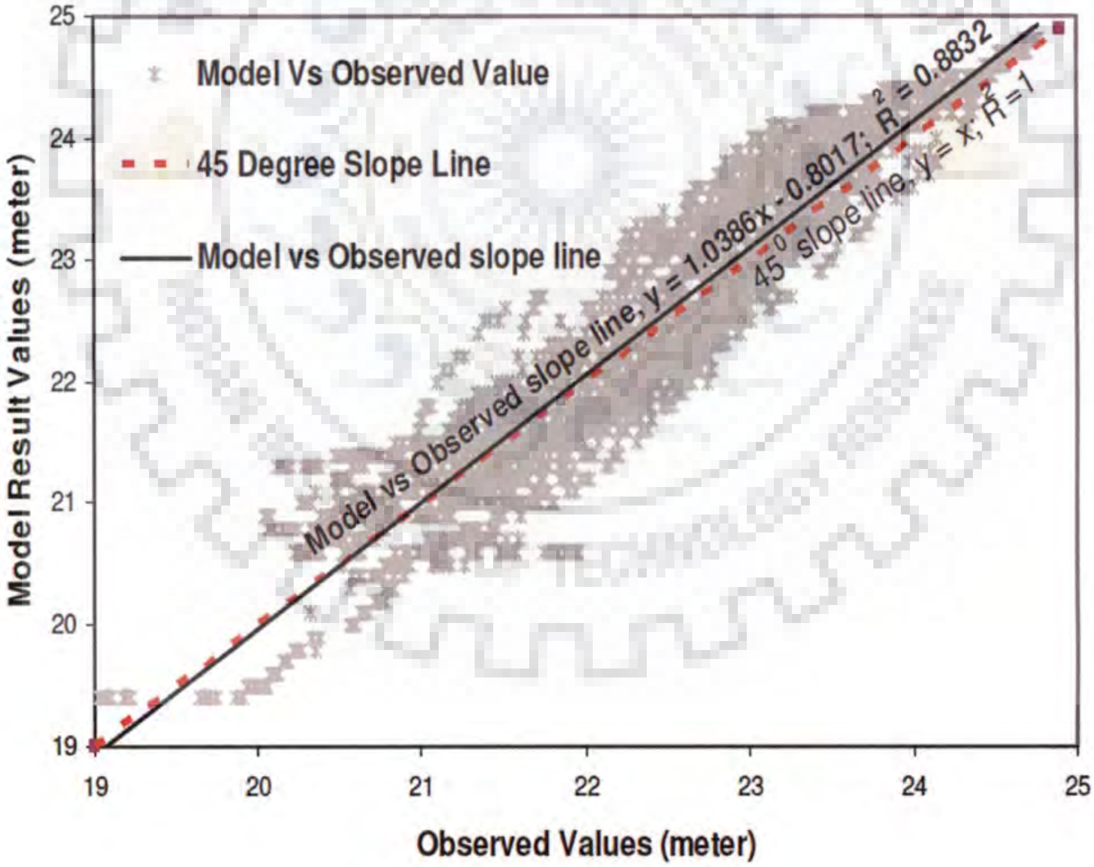


Figure 6.8: XY plot of model river stage vs observed river stage considering monsoon period at Chilmari

Table 6.4: Statistical parameter for comparison of model result for monsoon period only

SN	Statistical Parameters	Expected Values	Obtained from Observed and Result Values for each year								Averaged
			1996	1997	1998	1999	2000	2001	2002	2003	
1	Relative Bias	0.00	0.01	-0.01	0.01	0.01	0.00	-0.01	0.00	-0.01	0.00
2	MAE	0.00	0.29	0.37	0.38	0.31	0.39	0.21	0.40	0.33	0.34
3	RMAE	0.00	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.02
4	EI	1.00	0.97	0.74	0.87	0.81	0.81	0.92	0.85	0.83	0.85
5	Correlation Coefficient	1.00	0.95	0.91	0.96	0.95	0.94	0.98	0.94	0.94	0.95

The resultant time series of discharge was also compared with the observed discharge at Kaunia (Chainage 79,790 meter of the river Jamuna) for the monsoon period only and is shown in the Figure 6.9. The average values of statistical parameters such as relative bias (RB), Mean absolute error (MAE), Root mean absolute error (RAME), Efficiency Index (EI), and Coefficient of Correlation were then compared with the expected value of these parameters and found satisfactory. So, it may be concluded that the model results are calibrated and validated very well for the monsoon period.

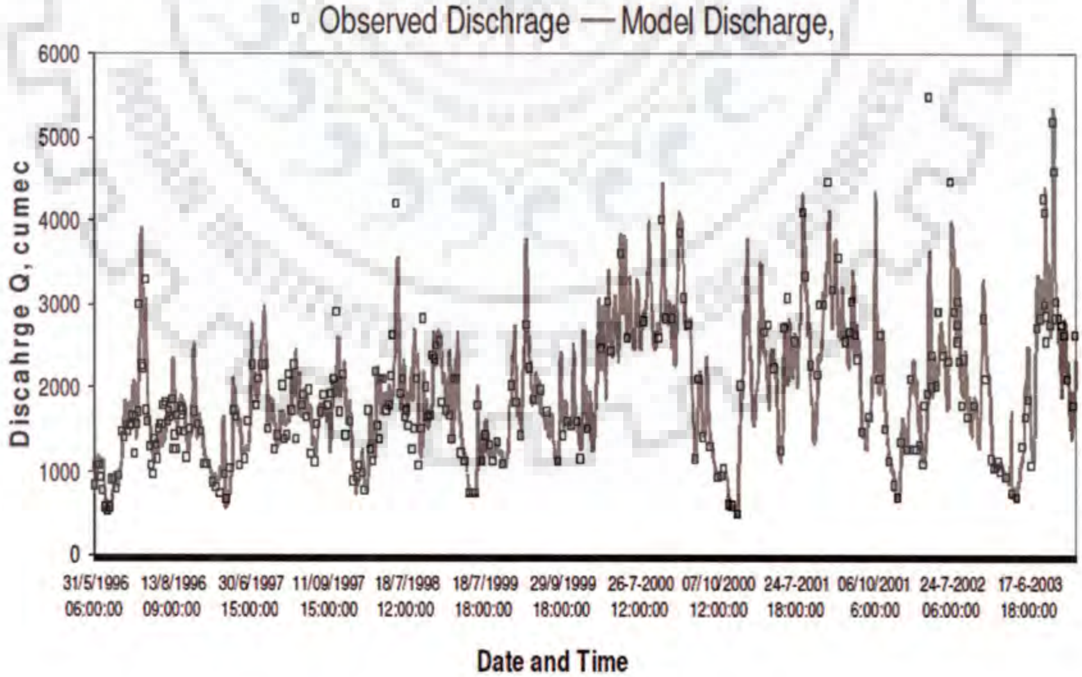


Figure 6.9: Graphical comparison of model results. Solid line represents simulated discharges (30 minutes time step) and the squares represents observed (low frequency and irregular time steps) discharge data at Kaunia for monsoon period only.

6.4 Development of rating curve equation

Moseley and McKercher (1993) described the general form of the rating curve as given in following equation (6.5)

$$Q = C(h + a)^N \quad (6.5)$$

Where Q = discharge

C and N = constants

h = stage

a = stage at which discharge is zero

Values of N for different cross-section shapes are

Rectangular N = 1.67 (assuming width < 20 depth)

Parabolic N = 2.17 (assuming width > 20 depth)

Triangular N = 2.67

Natural channels are generally parabolic in cross section, which is why about 2 for the N may be considered. Lohani et al. (2006, 2007) has done research for developing the stage discharge relationship curve. From the model result file, rating curve for discharge verses stage time series at Chainage 78,645 m of the Teesta river has been extracted.

The equation of the rating curve was developed by fitting with the time series of discharge vs river stage computed from the model results for monsoon period. This computed time series from developed equation has been compared with the corresponding time series of rating curve. The statistical error parameters such as multiplicative bias, relative mean absolute error, and coefficient of correlation were calculated as 1.06, 0.06, and 0.95, respectively, which are significantly close to the expected values 1.00, 0.00, and 1.00. Therefore the calibrated rating curve equation (6.6) is

$$Q = 116\,(h - 26.2)^{2.33} \quad (6.6)$$

Where Q is discharge (in m^3/sec) and h is river stage in meter.

6.5 Flood stage computation

Using rating curve equation, the flood stage for 25-, 50-, and 100-year return periods were calculated as 32.43, 32.66, and 32.86 m, respectively. The above results are useful for calculating the extent of the flooding for 25-, 50-, and 100-year return periods for flood risk analysis, flood zoning, and vulnerability assessment. The water resources engineers and hydrologists may find the results of flood stages useful for the flood control projects too.

6.6 Conclusions

A study was conducted in the Teesta subcatchment in Bangladesh for determining design flood flows and corresponding flood stages for different return periods using frequency analysis and MIKE11 model. Different distribution functions of frequency analysis were tested for their goodness of fit. The observed discharge data at Kaunia on the river Teesta was used for estimation of design flood. The Pearson Type III distribution was found best fitted by Kolmogorov-Smirnov, D-index, and L-Moment Diagram Ratio tests and accordingly 25-, 50-, and 100-year return periods design floods were computed. The river network of Teesta River was extracted from SRTM 90m DEM. The river network of Teesta subcatchment was then simulated by MIKE11 NAM and HD model. The resultant time series of river stage was then compared with corresponding observed values. From the model, a stage-discharge relationship (Q-h) curve and respective equation were developed for Kaunia station on the river Teesta. The developed equation determines the corresponding flood stage of estimated flood flow of 25-, 50-, and 100-year return periods. The resulting flows and stages will be useful to design hydraulic structures, prepare flood extent maps, to assess vulnerability of flood damage for different return periods, and provide flood forecasting for early warning of floods. The approach presented would be applicable to similar river basin systems where data are limited and scarce.

Note: Some repetitions in the sections on study area and description of MIKE11 model have intentionally been retained to maitain the continuity and readability of the contents of this chapter.

Chapter 7 - Assessment of Existing Early Flood Warning Dissemination System of Bangladesh

7.0 Introduction

Dissemination of forecasts to the affected end users is an important link in any flood forecasting setup. The flood forecasts should be disseminated in a timely manner and in understandable form. Moreover, the affected people, who are mostly uneducated, poor, and simple should believe the forecast and should act appropriately. Behavioral aspects of the affected people also play an important role in the success of any EFWDS.

Despite several advances in the flood forecasting system in Bangladesh, the existing system often underperforms because the warning, dissemination, and response of the end users are unsatisfactory (Chowdhury, 2005).

The present study has been taken up with the objective to critically assess the existing early flood warning dissemination system (EFWDS) of Bangladesh and suggest suitable improvements in this system based on review of literature, interaction with officials of various organizations involved in flood forecasting and dissemination, and interaction with the flood affected people of Dhobaura and Shibalaya sub-districts in Bangladesh.

7.1 Concept of early flood warning systems

The purpose of an early warning system is to provide information and warnings so that actions can be taken to protect lives and properties of the affected people. Forecasts and warnings must reach to the users without any delay and with sufficient lead-time to permit response actions to take place (ISDR, 2005). The progressive development of forecasting system can't be a success without success of the dissemination phase of the warning process. In spite of that, due to different reasons, early flood warning dissemination receives less attention than desirable (Parker, 1987).

The need for early warning system is recognized by Govt. of Bangladesh and the same has also been included in the National Water Policy of Bangladesh which states, "……through its responsible agencies, the Government will develop early warning and flood proofing systems to manage natural disasters like flood and drought" (GoB, 1998).

7.2 Existing EFWDS in Bangladesh

The Flood Forecasting and Warning Centre (FFWC) was established in 1972. This centre developed a comprehensive system for collection, processing and transmission of data, preparation of flood forecasts and warnings on a daily basis and dissemination of forecasts and warnings to various government and non-government organizations, media groups and other concerned parties over the years. From establishment through present, EFWDS of Bangladesh has been improved under several projects as explained in subsequent section.

7.2.1 Consolidation and strengthening of flood forecasting and warning services (CSFFWS)

The CSFFWS Project, from 2000 to December 2006 (BWDB and DHI, 2006), was executed by FFWC with the support of Danish Hydraulics Institute for Water and Environment (DHI) in association with Bangladesh Disaster Preparedness Centre (BDPC). The objectives of the project were (1) Development of flood forecast and inundation models (2) Dissemination of flood forecast information and warning messages, and (3) Institutional capacity building.

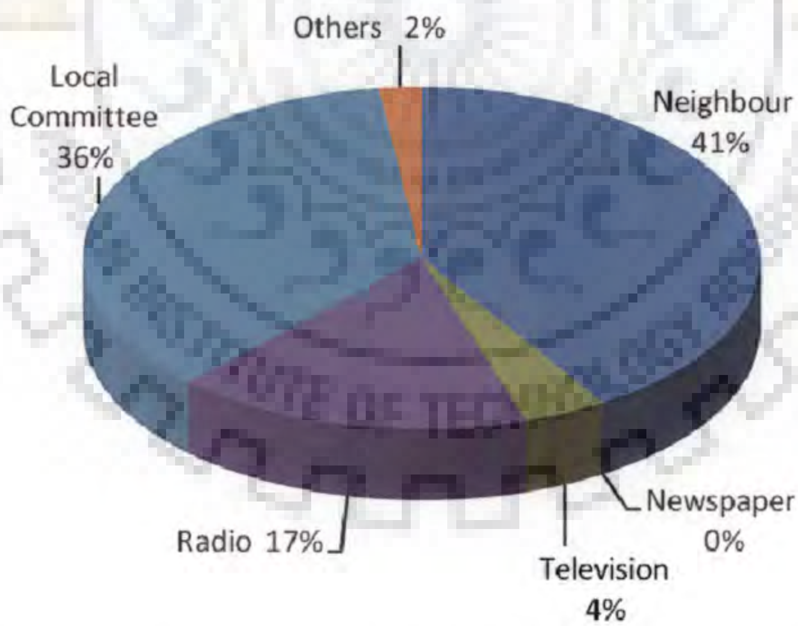


Figure 7.1: Feedback from affected people about media of warning dissemination conducted by NGO during 2000-2002 under CSFFWS

A study was made by the FFWC under CSFFWS to assess the response to its information by the people living in the flood-prone areas. The flood-affected people have indicated that they are receiving little information about flood onset through the existing warning dissemination media like television, newspaper, and radio as shown in Figure 7.1. This condition persists despite the fact that the technology of flood forecasts in Bangladesh, as in many other countries, has reached a highly sophisticated level. This aspect of flood information dissemination needs serious attention (Bhuiyan, 2006).

7.2.2 Environmental monitoring and information network (EMIN)

EMIN project (2000 to 2007) is the information network for coordination between key decision makers by monitoring the flood related disasters in Brahmaputra-Jamuna river basin. It functions in the national and local level by analysing Flood Maps in the national extents and River Flood Situation Maps in the local extent. EMIN carried out extensive information assesment (ICTDG and CEGIS, 2004) and then developed a system to bring information of onset floods to communities living in the flood plain. Community level flood information was calculated using the WATSURF programme developed under the CFIS project. The flood information (Flood Level) was communicated to communities using different media such as SMS on mobile phones, a system of different flags displayed at prominent places, loudspeakers, messangers etc., EMIN recommended (1) use of high resolution DEM, (2) development of flash flood warning system, (3) augmentation of lead time or warning messages, (4) strengthening of institutional linkage and information sharing among all concern organization, (5) development of mode of dissemination to reach women, and (6) raising awareness of local level institutions on how to use flood forecasts and warning effectively for floods prepardness.

7.2.3 Community flood information systems (CFIS)

CFIS project (2001 to 2006) developed GIS based flood forecasting information software named WATSURF to disseminate information on flood extent, duration, and depth of water to the community before the flood occurs. The forecasted results of FFWC were used as input in WATSURF (CEGIS, 2005). CFIS project disseminated flood warning from WATSURF to three micro pilot areas (known as mouzas). The CFIS project raised awareness amongst local people about the flood forecasts and warnings. Flood management committee were formed in the community level involving local aged elites, local government elected representatives and officials, and non-government organizations (Martin et al., 2006). Some individuals were selected in the community to serve as the operators to receive a daily text message with flood warnings and operate the flag system and bulletin board to inform the community of the flood warning. The message and symbols were designed with active participation of the local people (BDPC, 2003). The CFIS dissemination model varried slightly from the dissemination model used by EMIN. For example, CFIS relied entirely on local volunteers to disseminate flood information. CFIS showed that local organizations are capable of supporting the system and dissemination of flood warnings to all socio-economic groups.

7.3 Institutions related with EFWDS in Bangladesh

BWDB, under Ministry of Water Resources (MoWR), maintain FFWC which is the key entity for handling flood forecasts and warning system. Hydrology Directorate of BWDB and the Bangladesh Meteorological Department (BMD) under Minstry of Defence (MD) are prime organisations which furnish hydrological and meteorological data, respectively for the forecasting models. The Disaster Management Bureau (DMB) is an important organisation for respons and prepardness against the onset of floods under Ministry of Food and Disaster Managemnt (MFDM). These are some Research and Development organisations working with floods and flood forecasting. The organisations were visited by the author to review their activities related to flood forecasting, and obtained their views on possible improvements in existing flood forecasting and warning system.

FFWC disseminates the flood warning messages to the national level as well as local level through electronic Media, newspapers, and their own websites. FFWC sends the warning message as bulletins to the highest authority of the government, that is, Office of President of the Republic, concerned Ministries, Disaster Management Bureau (DMB), some NGOs, concerned research institutes and District Administrations. Local Government and local admisitration are not considerded by FFWC.

The critical assessment of roles of different organizations indicated the following:

- Shortage of funds and lack of leadership for disseminating meaningful flood warnings to communities and infrastructure managers,
- Insufficient lead time for flood warnings,
- Inadequate maintenance and upgrading of existing flood forecasting and warning system,
- Deficiencies in the accuracy and reliability of forecasts,
- Limited coverage,

- Flood warnings not understandable by many potential end users, and
- Inadequate coordination and feedback; and lack of ownership of the overall EFWS.

7.4 Case studies

Two case studies have been conducted for two different types of flood prone areas in Bangladesh. The studies were undertaken to determine whether or not the communities were aware of flood and receive early warning of floods. The objective was also to prepare local level authorities to disseminate the warning to the communities as well as to prepare the people for flood fighting response. The survey was conducted during the flood season of 2009. Two flood vulnerable areas namely Dhobaura, a flash flood prone area in Mymensingh district and Shibalaya, a river flooding area in Manikganj district were selected. The location of these two areas are shown in Figure 2.4 and Figure 2.5 in Chapter 2.

7.4.1 Methodology for the case studies

The methodology of this study is based on the survey of the opinion of the communities. For this purpose easily understandable questionnaires were prepared. The questionnaires were first pre-tested in the same area to understand whether people can respond easily with interest or not and whether there is any short-fall in the questionnaires. Total of twelve questions were placed before the vulnerable communities to get the information regarding the early flood information system. The questionnaires were prepared in Bengali language. However, the English version of the questionnaires along with Bengali language are given herein. The survey was conducted during August and September, 2009. Officials involved with this survey were: Mr. Nasirudding Khan, Chief Extension Officer, BWDB; Mr. Aminul Islam, the secretary of Union Parishad of Dhobaura; Mr. Runu Mia, the Secretary of Shibalaya Union Parishad; Mr. Manjurul Hoque, Field Officer, Social Welefare office Dhobaura; and Mr. Titu Nandi, Field Organizer of a NGO named World Vision. A total of 217 questionnaires were collected. These questionnaires were analyzed using Statistical Package for the Social Sciences (SPSS).

7.4.2 Questionnaires

7.4.2.1 Bengali version

বন্যা সতর্কবার্তা পদ্ধতি তৈরী কাজে জনগনের অংশগ্রহণ সংক্রান্ত প্রশ্নাবলির বিপরীতে আপনার পছন্দের উত্তরের উপর বা পাশে টিক (√) চিহ্ন দিন ।

১ । আপনার এলাকায় কি বন্যা হয়ে থাকে?

উত্তরঃ হ্যাঁ নিয়মিত/ অনিয়মিত/ না

২ । আপনার এলাকায় কি প্রকার বন্যা হয়ে থাকে?

উত্তরঃ বৃষ্টির পানি জমে/ পাহাড়ের ঢল নেমে/ নদীর পানি বৃদ্ধি পেয়ে/ অন্যকোন কারন থাকলে উল্লেখ করুনঃ ......

৩ । বন্যায় আপনার এলাকায় কি ধরনের ক্ষয়ক্ষতি হয়ে থাকে?

উত্তরঃ ব্যাপক ক্ষয়ক্ষতি হয়ে থাকে / সাধারন ক্ষয়ক্ষতি হয়ে থাকে/ কোন ক্ষয়ক্ষতি হয় না

৪ । বন্যা হলে আপনার এলাকায় কোন সম্পদের বেশি ক্ষয়ক্ষতি হয়ে থাকে?

উত্তরঃ কৃষিসম্পদ/ ঘরবাড়ী, রাস্তাঘাট ইত্যাদি/ হাঁসমুরগী, গরুছাগল ইত্যাদি/ মানবসম্পদ

৫ । প্রতি বৎসর বন্যার পূর্বে আপনার এলাকায় কি কোন সতর্কবার্তা দেওয়া হয়?

উত্তরঃ হ্যাঁ/ না

৬ । আপনার এলাকায় কি কোন বন্যার সতর্কবার্তা প্রয়োজন আছে?

উত্তরঃ হ্যাঁ/ না

৭ । আপনার এলাকায় কি কোন বন্যার সতর্কবার্তায় কি কোন উপকার হয় বা হবে বলে মনে করেন?

উত্তরঃ হ্যাঁ/ না

৮ । সতর্কবার্তায় বন্যার পরিমানের (বন্যার পানির গভীরতার) নিম্নোক্ত কোন ধরনের তথ্য থাকলে আপনি এবং আপনার এলাকার মানুষ উপকৃত হবে বলে আপনি মনে করেন?

উত্তরঃ নদীর পার হতে কত ফুট উপর পর্যন্ত/ নদীর পার হতে কত হাত বা আঙ্গুল/ কোন খুটির নির্দিষ্ট অংশ পর্যন্ত/ আপনার নিজস্ব কোন প্রস্তাব থাকলে উল্লেখ করুনঃ ....

৯ । সতর্কবার্তায় নিম্নোক্ত কোন ধরনের তথ্য থাকলে আপনি বা আপনার এলাকার জনসাধারন বন্যার ব্যপকতা (কত এলাকা জুড়ে বন্যা হবে) সম্বন্ধে ধারনা বেশি পাবেন ।

উত্তরঃ থানা ম্যাপের উপর বন্যার বিস্তৃতি/ ইউনিয়ন ম্যাপের উপর বন্যার বিস্তৃতি/ মৌজা ম্যাপের উপর বন্যার বিস্তৃতি/ আপনার নিজস্ব কোন প্রস্তাব থাকলে উল্লেখ করুনঃ ....

১০ । সতর্কবার্তা কোন মাধ্যমে প্রচার করলে আপনি তাড়াতাড়ি জানতে পারবেন ।

উত্তরঃ রেডিও এবং টিভি/ খবরের কাগজ/ মোবাইল ফোনে এসএমএস/ ভয়েসমেইল

১১ । সতর্কবার্তা কার নিকট প্রেরণ করলে তিনি আপনার এলাকার জনগনের নিকট তাহা দ্রুত প্রচার করবেন ।

উত্তরঃ সংসদ সদস্য/ জেলা প্রশাসন/ উপজেলা পরিষদের চেয়ারম্যান/ ইউনিয়ন পরিষদের চেয়ারম্যান/ এনজিও/ মসজিদের ইমাম/ অন্য কেহ থাকলে তাহা উল্লেখ করুনঃ ....

১২ । সতর্কবার্তা কার নিকট প্রেরণ করলে আপনি বন্যার ক্ষয়ক্ষতি এড়াতে দ্রুত ব্যবস্থা নিতে সহায়তা পেতে পারেন ।

উত্তরঃ সংসদ সদস্য/ জেলা প্রশাসন/ উপজেলা পরিষদের চেয়ারম্যান/ ইউনিয়ন পরিষদের চেয়ারম্যান/ এনজিও/ অন্য কেহ থাকলে তাহা উল্লেখ করুনঃ ....

আপনার নাম .... বয়স ....

পেশা .... পিতার নাম ....

ঠিকানা ....

7.4.2.2 English version

Please put the right mark (√) on your option(s) among/between the answers of questionnaires for people's participation to "Develop the Early Flood Warning Methodology" as given below:

1. Would you face any flood in your area?

   Answer: Yes regular/ Irregular / No

2. Please mention the type(s) of flood(s) in your area

   Answer: Rain fed flood/ Flash flood/ River flood /Please mention if there is/are any other reason(s) for flooding in your area:...

3. Provide the quantitative magnitude of the damages in your area.

   Answer: Immense damage/ Normal damage/ Not at all

4. Which type(s) of property (ies) is (are) under threat by flood (if occurred) in your area?

   Answer: Agricultural products/ Houses and communications/ Poultry and cattle / Human life

5. Is there any early flood warning in your area?

   Answer: Yes / No

6. Would you need any early flood warning in your area?

   Answer: Yes / No

7. Would you believe that early flood warning would be benefited in your area?

   Answer: Yes / No

8. Which type(s) of information will be easy understanding to magnify the flood depth in your area to response the floods?

   Answer: Flood depth in feet above the river bank level/ flood depth in hands or fingers above the bank level/ marking in a reference vertical post or pillar/ Please mention if there is any other option by you:..............................

9. Which type(s) of information will be easy understanding to magnify the flood extent in your area to response the floods?

   Answer: Flood map for Sub-district level / flood map for Union level/ flood map for Village (Mouza) level/ Please mention if there is any other option by you:..............................

10. Early flood warning will be useful to you if it is disseminated through

    Answer: Radio and TV/ Newspaper/ SMS by mobile phone/ Voice mail by mobile phone

11. Early flood warning will be disseminated properly if it is sent to the authority of

    Answer: Member of Parliament/ District Administration/ Upazela Chairman Parishad/NGO/Imam of Mosque/any other authority by your opinion:..........................

12. Flood damage would be reduced if the early flood warning message could be sent to

    Answer: Member of Parliament/ District Administration/Upazela Chairman Parishad/NGO/ any other authority by your opinion:.....................

Your Name: .... Age:

Your occupation: .... Your father's Name:.........Your Address:......................

7.4.3 Analysis of survey results

In Dhobaura and Shibalya Sub-districts, the number of respondents were 117 and 100 respectively. The age of respondents varied from 17 to 90 years in Dhobaura and from 17 to 78 years in Shibalaya. The mean and standard deviation of the age of the respondents are 50.65 and 16.91 in Dhobaura and 46.13 and 13.72 in Shibalaya. The occupation distributions of the respondents of both areas are given in the Figure 7.2.

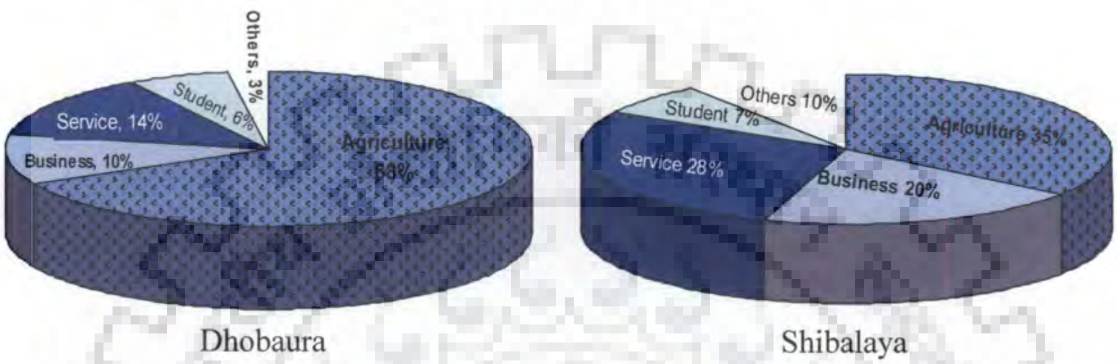
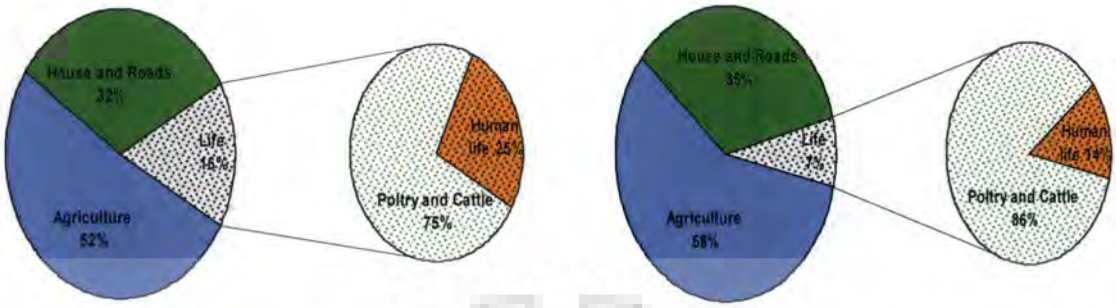


Figure 7.2: Occupation of respondents.

The survey has illustrated that the people are aware of the floods in their areas. 93.2% of respondents in Dhobaura and 98% of respondents in Shibalya have given their opinion that flood is a regular phenomenon in their area. They are also very much aware of the causes of floods. About 71% of persons from Dhobaura have opined that flood in their area is flash flood and 90% of Shibalaya respondents knew that it is river flood in their area (Table 7.1). More than 93% and 99% respondents in Dhobaura and Shibalaya respectively have assessed that their area is vulnerable to enormous flood damages. Figure 7.3 shows vulnerability statistics of life and properties. 16% and 7% respondents feel danger to life in Dhobaura and Shibalaya, respectively. More than 50% of the respondents of both areas (Dhobaura 52% and Shibalaya 58%) are worried for the loss of their agriculture due to flood every year. Response against no damage was absent in the collected data.

Table 7.1: Response of local people about the causes of flood in their area

Causes of Flood					
Data Quality	Selection of event causing flood	Frequency of Response		Percent of response	
		Dhobaura	Shibalya	Dhobaura	Shibalya
Valid	Rain water	6	6	5.1	6
	Flash flood	83	4	70.9	4
	River flood	9	90	7.7	90
	Total respondents	117	100	100	100



Dhobaura Shibalaya

Figure 7.3: Vulnerability statistics of life and properties.

Under this study, respondents have been asked whether or not they are receiving any warning message from any corner. Response against this question is not satisfactory whereas FFWC has been running since 1972. Among total respondents, 93% in Dhobaura and 79.4% in Shibalaya do not know about the warning message from FFWC. Table 7.2 shows the statistics of collected data about the availability of warning message. People of the areas have been found very keen to receive the warning message to save their properties and take safety measures against floods. Figure 7.4 shows the response of respondents in favour of warning message dissemination and 96% and 98% of them in Dhobaura and Shibalaya respectively think that warning message would be beneficial for them to save the damages.

Table 7.2: Response statistics of dissemination of present warning message by FFWC

Present Situation of Warning Message Dissemination					
Data Quality	Availability of Warning Message	Frequency of response		Percent of response	
		Dhobaura	Shibalaya	Dhobaura	Shibalaya
Valid	Available	8	20	6.9	20.6
	Not available	108	77	93.1	79.4
	Total	116	97	100	100
Missing		1	3	-	-
Total Respondents		117	100	-	-

Dhobaura Shibalaya

Figure 7.4: Response (in %) of respondent in favour of warning message dissemination

Dhobaura and Shibalaya are rural areas and internet is not easily accessible. Moreover people know only local Bengali language. Most of the respondents are related to agriculture. So, the format of flood warning message should be designed in Bengali which is understandable by the local people. The results of survey about magnitudes and extent of flooding are presented in Table 7.3 and Table 7.4.

Table 7.3: Response in % in favour of different proposed format for *flood depth* warning message dissemination

Opinion for Format of Warning Message for Flood Depth					
Data Quality	Format of message for flood depth	Frequency of response		Percent of response	
		Dhobura	Shibalaya	Dhobura	Shibalaya
Valid	Flood depth in feet	37	82	32.5	24.5
	Flood depth In hands or fingers	32	10	28	10.3
	Flood depth by marking on vertical post or pillars	45	5	39.5	65.2
	Total	114	97		-
Missing		3	3	-	-
Total respondent		117	100	-	

Table 7.4: Response in % in favour of different proposed formats for *flood extent* warning message dissemination

Opinion for Format of Warning Message for Flood Extent Map					
Data quality	Format of message for flood map	Frequency of response		Percent of response	
		Dhobaura	Shibalaya	Dhobaura	Shibalaya
Valid	Thana map	39	9	34	9.1
	Union map	74	80	64.3	80.8
	Mousa map	2	10	1.7	10.1
	Total	115	99	100	100
Missing		2	1	-	-
Total respondent		117	100	-	-

The mode of dissemination of warning message is an important component of any early flood warning system. It depends on the end users, i.e. whether the end user is decision maker or local level flood victim. However, the survey has been conducted through the local level flood victims and, their opinion is that the Radio and TV would be the suitable mass media to receive the information in their area. Some people have selected SMS through mobile telephones rather than voice mail. Actually, they have selected the said media according to their knowledge and practices. Voice mail might be easier for the villager, but because of the lack of knowledge about the voice mail they have not selected it. Their response is shown by pie chart in Figure 7.5.

The respondents are familiar with the local institutions/organizations in their area. They have easy access to institutions/organizations like "Union Parishad", NGO, Upazila Parishad, Religious Key Installation, Member of Parliament etc. In this respect, they are interested to strengthen the local institutes according to their own perception and interest. Probably, the role of these institutes in their society has also been influenced by their decision and reflected in Table 7.5 and Table 7.6. Table 7.5 illustrates the mandate to the institutions/organizations for dissemination activities and Table 7.6 illustrates the mandate to the institutions/organizations for response and disaster management like flood fighting, relief, rescue etc., according to the warning message. Regarding dissemination activities, majority of the respondents opted for local government (Union Parishad) and Non-Government Organization (NGO).

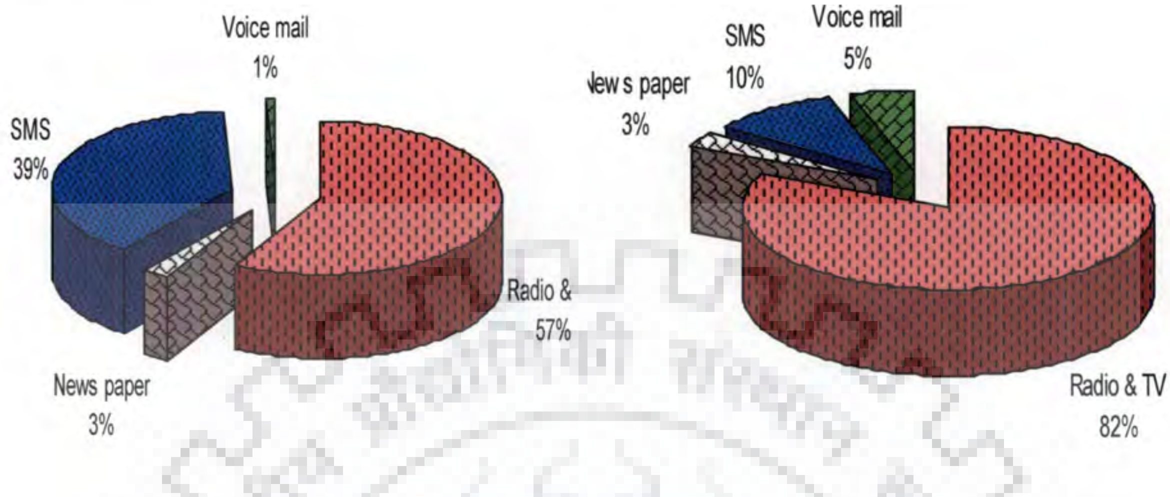


Figure 7.5: Response about suitable mass media for dissemination of warning message

Table 7.5: Response in favour of the institutions or organizations to disseminate the warning message to the end users.

Response to Institution/Organization for Dissemination of Warning Message					
Data Quality	Institutions/ Organizations	Frequency of response		Percent of response	
		Dhobaura	Shibalaya	Dhobaura	Shibalaya
Valid	Member of Parliament	19	3	16.4	3.0
	District Administration	3	2	2.6	2.0
	Upazila Parishad	7	6	6	6.0
	Union Parishad	28	70	24.1	70.0
	NGO	43	12	37.1	12.0
	Religious Key Stations	16	7	13.8	7.0
	Total	116	100	100	100
Missing		1	-	-	-
Total respondents		117	-	-	-

Table 7.6. Response in favour of the institutions or organizations to respond for disaster management according to warning message to the end users.

Response to Effective Authority too Flood Response					
Data Quality	Institutions/ Organizations	Frequency of response		Percent of response	
		Dhobaura	Shibalaya	Dhobaura	Shibalaya
Valid	Member of Parliament	22	12	18.8	12
	District Administartion	2	2	1.7	2
	Upalla Parishad	5	2	4.3	2
	Union Parishad	29	62	24.8	62
	NGO	59	22	50.4	22
	Total	117	100	100	100

The Dhobaura and Shibalaya areas are vulnerable to flooding which causes enormous damages. No localized EFWDS exist at present in these areas. FFWC disseminates the warning messages to the national level bodies but lacks in disseminating warning message for flood preparedness to the people in Dhobaura and Shibalaya areas. The local people feel that it would be beneficial if an EFWDS could be developed for their areas. They have suggested the format and language of the warning message. The flood depth marking on a post near the rivers would be understood by them and flood extent maps shown on Union Parishad map might make it easy to understand the probable damages of a flood. The participating people of the two areas feel that the Union Parishad, a micro level local government body, might be good local platform to disseminate the warning message to the communities of the end users. At present, in FFWC policy, Union Parishad is not included in the list where flood bulletins are sent. Warning message can be disseminated through Radio, TV, and SMS.

7.5 Conclusions and recommendations

The present study has been taken up with the objective to critically assess the existing EFWDS of Bangladesh and suggest suitable improvements in this system based on review of literature, interaction with officials of various organizations associated with flood forecasting and dissemination, and interaction with the flood affected people of Dhobaura and Shibalaya sub-districts in Bangladesh. Two survey studies have been conducted to collect the opinion of flood vulnerable communities to make the EFWDS more effective.

Based on the review of functions of the organizations associated with EFWDS, the following recommendations are made for better functioning of EFWDS:

- Better coordination among various organizations associated with EFWDS.
- Upgradation of knowledge, and skill of the staff associated with EFWDS.
- The feedback from the community level end users should be an integral part of EFWDS.

The survey conducted among the flood affected people of Dhobaura and Shibalaya indicated the following:

The Dhobaura and Shibalaya areas are vulnerable to flooding. No localized EFWDS exist at present in these areas. FFWC disseminates the warning messages to the national level bodies but do not disseminate the same to the people in Dhobaura and Shibalaya areas. The EFWDS is recommended to be developed for these areas with warning messages in local language through Radio, TV, and SMS. The flood depth marking on a post near the rivers and flood extent maps shown on Union Parishad map is recommended for better understanding and minimization of flood damages. The Union Parishad, a micro level local government body, is perceived to be a good platform to disseminate the warning message to the end users. At present, in FFWC policy, Union Parishad is not included in the list where flood bulletins are sent.

Chapter 8 - Conclusions and Recommendation for Further Work

8.0 General

The present study has been taken up with the broad objective to develop the methodology for improved flood forecasting and warning system suitable for Bangladesh, where availability of hydrometeorological data is very limited, using the web resources available in public domain and recent developments in hydrological modeling and GIS technology. The study involve the use of following methods:

(i) Extraction of river network and catchment boundary using 3-arc second SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) and GIS (Geographical Information System) application,

(ii) Evaluation of statistics of ECMWF (European Centre for Medium-range Weather Forecasts) and TRMM (Tropical Rainfall Measurement Mission) rainfall data for flood studies,

(iii) Development of flood forecasting system using MIKE11 NAM, HD, and FF modelling and ECMWF data for increasing the lead time and minimizing the forecast errors,

(iv) Estimation of design flood discharge and flood levels using L-moments based methods and different modules of MIKE11,

(v) Assessment of existing early flood warning dissemination system based on literature review, interaction with associated organizations and feedback from end users.

The conclusions and recommendations drawn from various studies presented in different chapters are summerised in following sections.

8.1 Limitation of 90m SRTM DEM in drainage network delineation using D8 method

A study has been undertaken to evaluate the performance of 90 m SRTM DEM in delineation of drainage network using Hydrology tool of ArcGIS 9.3 in the flat terrain of Bangladesh. Twelve catchments have been selected from the five hydrological zones of Bangladesh. It is concluded that in flat terrains, having a slope flatter than 1:2850, delineation of drainage network must be carried out carefully using the Hydrology tool of ArcGIS 9.3 software that uses the D8 method for delineation of drainage pattern and catchments. It is also recommended that other techniques excluding D8 method as implemented in ArcGIS 9.3, should be experimented with before a general conclusion about the use of SRTM data in flat terrains could be drawn.

8.2 Evaluation of ECMWF and TRMM rainfall data for flood studies

ECMWF and TRMM rainfall data have been downloaded and evaluated for their potentiality in flood studies using the observed rainfall data of the years 2004 and 2006 for Dinajpur, Rangpur, and Sylhet stations in Bangladesh. The visual verification, yes/no-dichotomous verification and continuous variables verification methods have been used. The results of the analysis indicate the potential use of both ECMWF and TRMM for flood studies.

The ECMWF provides the rainfall data in advance and hence can be used in flood forecasting studies to increase the forecast lead time. Both ECMWF as well as TRMM rainfall data may be used in flood estimation studies where observed rainfall data are not at all available. However, such studies should be taken up with more number of stations and more length of data to develop the relationships between observed rainfall and estimated rainfall by ECMWF or TRMM. The supremacy of either of the methods of rainfall estimation over the other method could not be established. The ECMWF forecasted rainfall data have been used in the developed Jamuneswari Flood Forecasting System (JFFS) for augmentation of lead time.

8.3 Development of Jamuneswary flood forecasting system

In this Chapter flood forecasting, JFFS has been developed by calibrating and validating MIKE11 NAM, HD, and FF Module. The MIKE11 NAM model has been calibrated for the years 2003 to 2005. The MIKE11 hydrodynamic model has been integrated with NAM model to improve the results by tuning Manning's coefficient.

The 24-, 48-, and 72-hour forecasted ECMWF rainfall data for 2006 have been used in the JFFS for flood forecasting in the Jamuneswari catchment area. The results show that with the increase of forecast lead-time, the accuracy decreases.

For increasing the accuracy of flood forecasting results, the JFFS has been updated using MIKE11 FF module producing satisfactory results. The following are suggestions for further improvement of JFFS:

- The existing network of hydrometerological stations should be scientifically designed to improve the results. The raingauges of key stations should be replaced by automatic raingauges for better results.
- In absence of evapotranspiration data, evaporation data of nearby stations have been used in the model. Use of actual evapotranspiration data shall improve the efficiency of JFFS.
- Old cross sections which were measured 12 years back have been used in the model. These cross sections need to be replaced by latest measurements for further improvements of the results.
- The studies initiated in this thesis should continue for Jamuneswari catchment in future and such studies should be taken for other basins.

8.4 Estimation of design flow and stage using frequency analysis and MIKE11 modeling

A study was conducted in the Teesta subcatchment in Bangladesh for determining design flood flows and corresponding flood stages for different return periods using frequency analysis and MIKE11 model. Different distribution functions of frequency analysis were tested for their goodness of fit. The observed discharge data at Kaunia on the river Teesta was used for estimation of design flood. The Pearson Type III distribution was found best fitted by Kolmogorov-Smirnov, D-index, and L-Moment Diagram Ratio tests and accordingly 25-, 50-, and 100-year return periods design floods were computed. The river network of Teesta River was extracted from SRTM 90m DEM. The river network of Teesta subcatchment was then simulated by MIKE11 NAM and HD model. The resultant time series of river stage was then compared with corresponding observed values. From the model, a stage-discharge relationship (Q-h) curve and respective equation were developed for Kaunia station on the river Teesta. The developed equation determines the corresponding flood stage of estimated flood flow of 25-, 50-, and 100-year return periods. The resulting flows and stages will be useful to design hydraulic structures, prepare flood extent maps, to assess vulnerability of flood damage for different return periods, and provide flood forecasting for early warning of floods. The approach presented would be applicable to similar river basin systems where data are limited and scarce.

8.5 Assessment of existing early flood warning dissemination system of Bangladesh

The present study has been taken up with the objective to critically assess the existing EFWDS of Bangladesh and suggest suitable improvements in this system based on review of literature, interaction with officials of various organizations associated with flood forecasting and dissemination, and interaction with the flood affected people of Dhobaura and Shibalaya sub-districts in Bangladesh. Two survey studies have been conducted to collect the opinion of flood vulnerable communities to make the EFWDS more effective.

Based on the review of functions of the organizations associated with EFWDS, the following recommendations are made for better functioning of EFWDS:

- Better coordination among various organizations associated with EFWDS.
- Upgradation of knowledge, and skill of the staff associated with EFWDS.
- The feedback from the community level end users should be an integral part of EFWDS.

The survey conducted among the flood affected people of Dhobaura and Shibalaya indicated the following:

The Dhobaura and Shibalaya areas are vulnerable to flooding. No localized EFWDS exist at present in these areas. FFWC disseminates the warning messages to the national level bodies but do not disseminate the same to the people in Dhobaura and Shibalaya areas. The EFWDS is recommended to be developed for these areas with warning messages in local language through Radio, TV, and SMS. The flood depth marking on a post near the rivers and flood extent maps shown on Union Parishad map is recommended for better understanding and minimization of flood damages. The Union Parishad, a micro level local government body, is perceived to be a good platform to disseminate the warning message to the end users. At present, in FFWC policy, Union Parishad is not included in the list where flood bulletins are sent.

REFERENCES

Abbott, M.B. and Ionescu, F., (1967), "On the numerical computation of nearly-horizontal flows", Journal of Hydraulic Research, 5, pp. 97-117.

ADB-World Bank, (2004), "Emergency Flood Damage Rehabilitation Project", Joint ADB-World Bank damage and need assessment, Dhaka, November 2004.

Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., Rudolf, B., Schneider, S. Curtis, U., Bolvin, D., Gruber, A., Susskind, J., Arkin, P. and Nelkin, E., (2003), "The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present)", J. Hydrometeor., 4, 1147-1167.

Aitken, A.P., (1973), "Assessing Systematic Errors In Rainfall-runoff Models." Journal of Hydrology, 20, p 121-136.

Alam, J. B., (2000), "The Concept of Flood Shelter and its Planning to Cope with Flood", In implementing Hazard-Resistant Housing proceedings of the Third Housing and Hazards International Conference held in Dhaka, Bangladesh, 24-26 November 2000 and Exeter, UK, 4-5 December 2000, edited by Hodgson, Seraj and Choudhury, pp. 217-224.

Alarcon, V.J., and O'Hara, C., (2006), "Using IFSAR and SRTM Elevation Data for Watershed Delineation of a Coastal Watershed", MAPPS/ASPRS 2006 Fall Conference November 6 – 10, 2006 * San Antonio, Texas, USA.

Andersson, E., and J-N Thepaut, (2008), "ECMWF's 4-D var data assimilation system- the genesis and ten years in operation", ECMWF Newsletter No. 115, pages 8-12. (available at http://www.ecmwf.int)

Asiatic Society of Bangladesh, (2006), "Banglapedia: National Encyclopedia of Bangladesh", Ministry of Cultural Affairs, Govt. of Bangladesh.

BBS (Bangladesh Bureau of Statistics), (2002), Ministry of Planning, Government of Bangladesh, Dhaka, 2002.

BDPC, (2003), "Community Needs Assessment: Floods Vulnerabilty and Risk Reduction through Community based Flood Information Systems (CFIS)", Bangladesh Disaster Prepardness Centre, Dhaka, Bangladesh.

Bechtold, P., Chaboureau, J. P., Beljaars, A., Betts, A.K., Koehler, M., Miller, M., Redelsperger, J. L., (2004), "The simulation of the diurnal cycle of convective precipitation over land in a global model", Q.J.R. Meteorol. Soc. 130: 3119-3137.

Bedient, P. B. and Huber, W.C., (2002), "Hydrology and floodplain analysis", 3rd ed. Prentice Hall, Upper Saddle River, NJ 07458.

Benke, K.K., Lowell, K.E. & Hamilton, H.J., (2008), "Parameter uncertainty, sensitivity analysis and prediction error in a water-balancehydrological model", Math Comput Model 2008, 47, (11–12), 1134–1149.

Bergman, M. J., and Delleur, J. W., (1985), "Kalman filter estimation and prediction of daily stream flows. I: Review, algorithm, and simulation experiment", Water Resour. Bull., 21_5_, 815–25.

Beven K. Prophecy, (1993), "Reality and uncertainty in distributed hydrological modeling", AdvWater Resour, 16, (1), 41–51.

Bhang, K.J. and Schwartz, F., (2008), "Limitations in the Hydrologic Applications of C-Band SRTM DEMs in Low-Relief Settings". IEEE Geo-Science and Remote Sensing Letters, Vol. 5, No. 3, pp. 497-501.

Bhuiyan, M.S., (2006), "Flood Forecasting, Warning and Response System", Proceedings of National Workshop on Options for Flood Risks and Damage Reduction in Bangladesh, 7-9 September 2004.

Bronstert, A. and Bardossy, A., (2003) "Uncertainty of runoff modelling at the hillslope scale due to temporal variations of rainfall intensity", Phy Chem Earth, Parts A/B/C, 28, (6–7), 283–288.

Brown, B.G., Thompson, G., Bruintjes, R.T., Bullock, R., and Kane, T., (1997), "Intercomparison of in-flight icing algorithms. Part II: Statistical verification results", *Wea. and Forec.*, 12, 890-914.

Butts, M.B., Payne, J.T., Kristensen, M. & Madsen, H., (2004), "An evaluation of the impact of model structure on hydrological modeling uncertainty for streamflow simulation", J. Hydrol, 298, (1–4), 242–266.

BWDB and DHI, (2006), "Consolidation and Strengthening of Flood Forecasting and Warning Services", Final Report Volume-V – Project Extension Report, In association with IWM, NCG, Mott Macdonald, Aqua , BDPC, GKSS, Prip Trust, December 2006.

CEGIS, (2005), "Draft technical document on WATSURF Version 2.2", Ministry of Water Resources, Bangladesh.

CGIAR-CSI, (2008), "Applying GeoSpatial Science for Sustainable Future", CGIAR-Consortium for Spatial Information (CGIAR-CSI), (http://srtm.csi.cgiar.org/, 08/09/2008).

Chow, V. T., Maidment, D. R. and Mays, L. W., (1988), "Applied Hydrology", McGraw-Hill International edition.

Chowdhury, M.R, (2000), "An assessment of flood forecasting in Bangladesh: The experience of the 1998 flood", Natural Hazards. 22(2). pp. 139–163.

Chowdhury, M.R. and Ward, N., (2004), "Hydro-Meteorological Variabilty in the Greater Ganges-Brahmaputra-Meghna Basins" Int. J. Climatol. 24: 1495–1508 (2004).

Chowdhury, M.R., (2005), "Consensus Seasonal Flood Forecasts and Warning Response System – An Alternate for Flood Management in Bangladesh", Environmental Management 35:6, 716 ~725, Springer, DOI: 10.1007/s00267-004-0010-4.

Costa-Cabral, M., and Burges, S.J., (1994), "Digital elevation model networks (DEMON): Amodel of flow over hillslopes for computation of contributing and dispersal areas, Water Resour. Res., 30(6), 1681-1692.

Demeritt, D., Cloke, H., Pappenberger, F., Thielen, J., Bartholmes, J. & Ramos, M.H., (2007), "Ensemble predictions and perceptions of risk, uncertainty, and error in flood forecasting", Environ Hazards, 7, (2), 115–127.

Dhar, S. and Majumdar, A., (2009), "Hydrological Modeling of the Kangsabati River under Changed Climate Scenario: Case Study in India", Hydrol. Process. 23, 2394–2406 (2009), Published online 27 May 2009 in Wiley InterScience.

DHI, (2004), "MIKE 11 User & Reference Manual", Danish Hydraulic Institute, Denmark.

Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S. J. and Ropelewski, C. F., (2007), "Validation of Satellite Rainfall Products Over East Africa's Complex Topography," International Journal of Remote Sensing, 28(7), 1503–1526.

ESRI Inc., (2007), "ARC/INFO Windows Version 9.2", Environmental Systems Research Institute (ESRI), 380 New York Street, Redlands, California 92373-8100, USA.

Fairfield, J. and Leymarie, P., (1991), "Drainage networks from grid digital elevation models", Water Resour Res 27(5):709–717.

FFWC (Flood Forecasting and Warning Centre), (2005a), "Annual Flood Report", Bangladesh Water Development Board, Dhaka.

FFWC, (2005b), "Consolidation and strengthening of flood forecasting and warning services", Final Report, Volume II – Monitoring and evaluation, BWDB, Dhaka.

Fleming, G., (1975), "Computer Simulation Techniques In Hydrology", Elsevier: New York. Pp 18-53, 239-252.

Gabellani, S., Boni, G., Ferraris, L., VonHardenberg, J. & Provenzale, A., (2007), "Propagation of uncertainty from rainfall to runoff: a case study with a stochastic rainfall generator", Adv Water Resou, 30, (10), 2061–2071.

Georgakakos, K. P., (1986), "A generalized stochastic hydro meteorological model for flood and flash-flood forecasting 1. Formulation", Water Resour. Res., 22_13, 2083–95.

GoB (Government of Bangladesh), (1998), "FAP 25, flood modeling and management. Flood hydrology study", Main Report. Government of Bangladesh, Dhaka.

Google Inc., (2008), "Google Earth", 1600 Amphitheatre Parkway, Mountain View, CA 94043, United States.

Gupta, R. S., (1989), "Hydrology and Hydraulic system", Prentice Hall, Englewood cliffs, New Jersey 07632.

Haan, C.T., Johnson, H.P., and Brakensiek, D. L., (1982), "Hydrologic modeling of small watersheds", American Society of Agriculture Engineers, 2950 Niles road, St. Joseph, Michigan 49085 , USA.

Hancock, G.R., Martinez, C., Evans, K. G., and Moliere, D. R., (2006), "A comparison of SRTM and high-resolution digital elevation models and their use in catchment geomorphology and hydrology: Australian examples," Earth Surf. Processes and Landf., vol. 31, no. 11, pp. 1394–1412.

Hassan, A. J., Ab. Ghani, A. & Abdullah, (2006), "Development of Flood Risk Map using GIS for Sg. Selangor Basin", 6th International Conf. on ASIA GIS, University Teknologi Malaysia (UTM), 9-10 Mac.

Hirsch, R.M., Helsel, D.R., Cohn, T.A. and Gilroy.E.J., (1993), "Statistical Analysis of Hydrological Data", Handbook of Hydrology, Edited by Maidment, D.R., McGRAW-HILL, INC.

Horton, R.E., (1945), "Erosional development of streams and their drainage basins: Hydrological approach to quantitative morphology". Geol Soc Am Bull 56(3):275-370.

Hosking, J.R.M. and Wallis, J.R., (1993), "Some statistics useful in regional frequency analysis", Water Resources Research 29 (2), 271–281.

Hosking, J.R.M. and Wallis, J.R., (1997), "Regional Frequency Analysis: An Approach based on L-moments". Cambridge University Press, Cambridge, UK.

Hosking, J.R.M., (1990), "L-moments: analysis and estimation of distributions using linear combinations of order statistics". Journal of the Royal Statistical Society Series B, 52(1), 105-124.

Hossain, A.N.H.A., (2004), "The Impact of Flood on Bangladesh and Options for Mitigation: An Overview", Keynote Paper, Proceedings of National Workshop on Options for Flood Risks and Damage Reduction in Bangladesh, 7-9 September 2004.

Huffman, G. J., Adler, R.F., Arkin, P., Chang, A., Ferraro, R., Gruber, A., Janowiak, J., McNab, A., Rudolf, B., and Schneider, U., (1997), "The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset". Bulletin of the American Meteorological Society, Vol. 78, No. 1, pp. 5-20.

Huffman, G.J., Adler, R.F., Bolvin, D.T., Gu, G., Nelkin, E.J., Hong, Y. and Wolff. D.B., (2007), "The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales", Journal of Hydrometeorology, Volume 8, Issue 1. pp. 38–55, DOI: 10.1175/JHM560.1

Hurst, H.E., (1951),"Long term storage capacity of reservoirs", Trans.ASCE. 116:770-808.

ICTDG and CEGIS, (2004), "Flood and Erosion Information Needs Assessment Report", EMIN Implementation Phase, Ministry of Water Resources, Bangladesh.

ISDR (International Strategy for Disaster Reduction), (2005), Integrated Flood Forecasting, Warning and Response System, Guidelines for Reducing Flood Losses. (http://www.unisdr.org/eng/library/isdr-publication/flood-guidelines /isdr-publication-floods.htm, Dated 16/11/2008).

Jensen, S.K. and Dominique, J.O., (1988), "Extracting topographic structure from digital elevation data geographical information system analysis, Photogrammetric Engineering and Remote Sensing, 54 (11), pp. 1593-1600.

Jonch-Clausen, T and Refsgaard, J.C., (1984), "A mathematical modeling system for flood forecasting", Nordic Hydrology, 15, pp 307-318.

Jorgensen, G. and Host-Madsen, J., (1997), "Development of a Flood Forecasting. System in Bangladesh", Conference Proceedings, Operational Water Management Conference, Copenhagen, Denmark, Sept 2-6.

Kendall, M.G., (1975)," Rank correlation Methods". Griffin, London.

Kolmogorov, A., (1933), "Sulla Determinazione Empirica di una Leggé di Distribuzione", *G. Ist. Ital. Attuari*, 4, 83.

Kottegoda, M., (1980), "Stochastic water resources technology", John Wiley and Sons, New York.

Krzysztofowicz, R. and Herr, H.D., (2001), "Hydrologic uncertainty processor for probabilistic river stage forecasting: precipitation-dependent model", J Hydrol 2001, 249, (1–4), 46–68.

Krzysztofowicz, R., (2001), "Integrator of uncertainties for probabilistic river stage forecasting: precipitation-dependent model", J Hydrol, 249, (1–4), 69–85.

Kumar, R., Chatterjee, C., Kumar, S., Lohani, A. K. and Singh, R. D., (2000), "Development of regional flood frequency relationships using L-moments for South Bihar". Proc. of International Conference on Integrated Water Resources Management (ICIWRM), NIH, Roorkee, Ajay Printers and Publishers, December 19-21, 2000, Vol. 1, pp. 805-812.

Kumar, R., Chatterjee, C., Kumar, S., Lohani, A. K., and Singh, R. D., (2003), "Development of regional flood frequency relationships using L-moments for Middle Ganga Plains (Subzone 1-f) of India". Water Resources Management, Kluwer Academic Publishers, Netherlands, 17, pp. 243-257.

Kwaku, X. S. and Duke, O., (2007), "Characterization and frequency analysis of one day annual maximum and two to five consecutive days' maximum rainfall of ACCRA, Ghana", ARPN Journal of Engineering and Applied Sciences, Vol. 2, NO. 5, October 2007.

Lettenmaier, D.P. and Wood, E.F., (1993), "Hydrologic Forecasting", Hand Book of Hydrology, Edited by Devid R. Maidment, McGRWAW – HILL, INC.

Lohani, A.K., Goel, N.K., and Bhatia, K.K.S., (2006), "Takagi-Sugeno fuzzy inference system for modeling stage-discharge relationship", Journal of Hydrology, Vol. 131/1-2, pp. 146-160.

Lohani, A.K., Goel, N.K., and Bhatia, K.K.S., (2007), "Setting up stage-discharge-sediment concentration relationship using fuzzy logic", Hydrological Sciences Journal (in press).

Lye, L.M. and Lin, Y., (1993), "Long-term dependence in annual peak flows of Canadian rivers", Journal of Hydrology, 160 (1994) 89-103, Elsevier.

Maidment, D. R., ed. (2002), "Arc Hydro GIS for Water Resources", ESRI Press, Redlands, CA, 203 p.

Mann, H.B., (1945), "Non parametric tests against trend", Econometrica 13, 245-259.

Markar, M.S., Clark, S.Q., Yaowu, Min and Jing, Zheng, (2004), "Evaluation of Hydrologic and Hydraulic Models for Real-Time Flood Forecasting use in the Yangtze River Catchment", Australian Journal of Water Resources, Vol. 10, No. 1, 2006: 93-102.

Martin, T., Hassan, A., Rahman, S. and Wirthlin, K., (2006), "Vulnerbility and risk reduction through a community-based system for flood forecasting and monitoring", Paper presented to the 4th Annual Mekong Flood Forum", Siem Reap. 18-19 May.

McCuen, R. H. and Snyder, W. M., (1985), "Hydrologic Modeling: Statistical Methods and Applications", Prentice-Hall, Englewood cliffs, New Jersey 07632.

Meacham, I., (1968), "Correlation in sequential data – three sample indicators", Civ. Eng. Trans. Eng. Aust., CE10 (2): 225-228.

Mirza, M.M.Q., Warrick, R. A., Erocksen, N. J. & Kenny, G. J., (1998), "Trends and persistence in precipitation in the Ganges, Brahmaputra and Meghna river basins", Hydrological Sciences Journal, 43: 6, 845 — 858, DOI: 10.1080/02626669809492182.

Mishra, A., Anand, A., Singh, R. and Raghuwanshi, N. S., (2001), "Hydraulic Modelling of Kangsabati Main Canal for Preference Assessment", Journal of Irrigation and Drainage Engineering, Vol. 127, No. 1, January/February, 2001. ASCE, ISSN 0733-9437/01/0001-0027–0034.

Mishra, A., Singh, R. and Raghuwanshi, N. S., (2005), "Development and Application of an Integrated Optimization-Simulation Model for Major Irrigation Projects", Journal of Irrigation and Drainage Engineering, Vol. 131, No. 6, December 1, 2005. ©ASCE, ISSN 0733-9437/2005/6-504–513

Mitra, A.K., Bohra, A.K., Rajeevan, M.N., and Krishnamurti, T.N., (2009), "Daily Indian Precipitation Analysis Formed from a Merge of Run-Gauge Data with the TRMM TMPA Satellite Derived Rainfall Estimates", Journal of the Meteo. Society of Japan, Vo;. 87A, pp. 265-279, 2009, DOI:10.2151/jmsj.87A.265.

Moore, I.D. and Grayson, R.B., (1991), "Terrain-based catchment partitioning and runoff prediction using vector elevation data", Water Resources Research, 27(6), 1177-1191.

Moore, ID., O'Loughlin, E.M. and Burch, G.J., (1988), "A contour-based topographic model for hydrological and ecologica applications", Earth Surf. Process Landforms, 13, 305-320, 1988.

Mosley, M.P. and McKercher, A.I., (1993), "Streamflow", Handbook of Hydrology, Edited by Maidment, D.R., McGRAW-HILL, INC.

MoWR, (2008), Long Lead Flood Forecast Technology for Disaster Management, International Seminar Proceedings, September 2008 Version 1.0, GoB.

MSU (Michigan State University), (2008), "Watershed Characteristics", Class module-BE 481, College of Engineering, Michigan State University, USA. (http://www.egr.msu.edu/~northco2/BE481/WshedChar.htm, 12/09/2008).

Murphy, A.H., (1993), "What is a good forecast? An essay on the nature of goodness in weather forecasting", Wea. Forecasting, 8, 281-293.

Murphy, A.H., and Winkler, R.L., (1987), "A general framework for forecast verification" Mon. Wea. Rev., 115, 1330-1338.

Nash, J.E. and Sutcliffe, J.V., (1970), "River Flow Forecasting Through Conseptual Models", Part 1: A Discussion on Principals. Journal of Hydrology, V10, p 282-290.

Nielsen, S.A. and Hansen, E., (1973), "Numerical simulation of the rainfall runoff process on a daily basis", Nordic Hydrology, 4, 171-190.

Nurmi, P., (2003), "Recommendations on the verification of local weather forecasts", ECMWF Technical Report No 430.

O' Callaghan, J. and Mark, D.M., (1984), "The extraction of drainage networks from digital elevation data", Comput. Vision Graphics Image Processes 28(3), 323-344.

ODA and JICA, (1993), "North West Regional Study (FAP2)", The Regional Plan, Final Report, January 1993, Flood Plan Co-ordination Organization, Ministry of Water Resources, Government of Bangladesh.

Ojha, C. S. P., Bhunya, P., Berndtsson, R., (2008) "Engineering Hydrology", Publisher: Oxford Univ Pr (July 15, 2008)

Orlandini, S., Moretti, G., Franchini, M., Aldighieri, B. and Testa, B., (2003), "Path-based methods for the determination of nondispersive drainage directions in grid-based digital elevation models", Water Resour. Res., 39(6), 1144, doi:10.1029/2002WR001639.

Patro, S., Chatterjee, C., Mohanty, S., Singh, R. and Raghuwanshi, N.S., (2009), "Flood Inundation Modeling using MIKE FLOOD and Remote Sensing Data", J. Indian Soc. Remote Sens. 37:107–118., (DOI: 10.1007/s12524-009-0002-1).

Paudyal, G.N., (2002), "Forecasting and warning of water-related disasters in a complex hydraulic setting—the case of Bangladesh", Hydrological Sciences Journal, 47(S) S5-S18.

Paudyal, G.N., (2002a), "Transboundary Flood issues:(2). Regional Flood Forecasting-. dreams slowly becoming reality!", A presentation (www.mrcmekong.org/.../AFF3/Annex% 201.3%20 Presentations/ann1.3.3/ 7-Transboundary%20Mediation%20by% 20Guna.pdf, 16/05/2008).

Puente, C. E., and Bras, R. L., (1987), "Application of nonlinear filtering in the real time forecasting of river flows." Water Resour. Res., 23_4_, 675–682.

Quinn, P. F., Beven, K. J., Chevallier, P. and Planchon, O., (1991), "The prediction of hillslope flow paths for distributed modelling using digital terrain models", Hydrol. Processes, 5, 59– 80.

Rahman, M.M, Arya, D.S. and Goel, N.K., (2010), "Limitation of Application of 90m SRTM DEM in Hydrological Application/Analysis using D8 method in the Flat Terrain of Bangladesh", Applied Geometrics (Springer Link), DOI 10.1007/s12518-010-0020-2.

Rahman, M.M, Arya, D.S. Goel.N.K, and Dhamy, A.P., (2010b), "Design Flow and Stage Computation in the Teesta River, Bangladesh using Frequency Analysis and MIKE 11", J. Hydrologic Engg. http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000299.

Rao, R.A. and Hamed, H.K., (2000), "Flood frequency analysis". CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431. 350p.

Refsgaard J.C., (1997), "Validation and Intercomparison of Different Updating Procedures for Real-Time Forecasting", Nordic Hydrology, 28, pp 65-94.

Refsgaard, J. C., Havncd, K., Ammentorp, H. C., and Verwey, A., (1988) "Application of Hydrological Models for Flood Forecasting and Flood Control in India and Bangladesh", Elsevier Volume 11, Issue 2, June 1988, Pages 101-105, doi:10.1016/0309-1708(88)90043-7.

Refsgaard, J.C. and Ghanekar, V.G., (1986), "Flood Forecasting, Damodar". World Water, August 1986.

Refsgaard, J.C. and Knudsen, J., (1997), "Operational validation and interco.mparison of different types of hydrological models", Water Resources Research, 32(7), 2189-2202.

Rungo, M., Refsgaard, J.C. and Havno, K., (1989), "The updating procedure in the MIKE11 modelling system for real-time forecasting", Proceedings from the

International Symposium on Hydrological Applications of Weather Radar, Salford, UK, August 1989.

Seibert, J., and B. L. McGlynn, (2007), "A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models", Water Resour. Res., 43, W04501, doi:10.1029/ 2006WR005128.

Shrestha, L.D., (2000), "Flood estimation for Bagamati River at Pandhera Dhovan, Nepal", M.E. Dissertation, 27th International hydrology course, Department of Hydrology, University of Roorkee, India.

Sikka A.K. and Ringler, C., (2009) "Introduction to the Special Issue" Intl. J. River Basin Management Vol. 7, No. 2 (2009), pp. 107–110 © 2009 IAHR, INBO & IAHS.

Singh, V.P., (1994), "Elementary Hydrology", Prentice-Hall of India Private Ltd., New Delhi-110 001, India.

Sivakumar, B., Berndtsson, R., (2010), "Advances in Data-Based Approaches for Hydrologic Modeling and Forecasting", World ScientificPublishers, Singapore (in press).

Smith, J.A., (1993), "Precipitation", Handbook of Hydrology, Edited by Maidment, D.R., McGRAW-HILL, INC.

Stanski, H.R., Wilson, L.J. and Burrows, W.R., (1989), "Survey of common verification methods in meteorology", World Weather Watch Tech. Rept. No.8, WMO/TD No.358, WMO, Geneva, 114 pp.

Stephenson, D.B., (2000), "Use of the "*odds ratio*" for diagnosing forecast skill. *Wea. Forecasting*, 15, 221-232.

Strahler, A. N., (1952), "Hypsometric (area-altitude) analysis of erosional topology", Geological Society of America Bulletin, 63(11), 1117-1142.

Tarboton, D. G., (1997), "A new method for the determination of flow directions and upslope areas in grid digital elevation models", Water Resour. Res., 33(2), 309– 319.

The World Bank, (2002), "Bangladesh Disaster & Public Finance", World Bank Paper no-6. Dhaka, 2002.

Thepaut J. N., Andersson, E., Beljaars, A.C.M., Hortal, M., Janssen, P., (2005), "Two new cycles of the IFS: Cylce 26r3 and Cycle 28r1", ECMWF Newsletter 102: 26-35.

Todd, M. C., E: C. Barrett, M. J. Beaumont, and J. L. Green, (1995), "Satellite identification of rain days over the upper Nile river basin using an optimum infrared rain/no-rain threshold temperature model", J. Appl. Meteorol., 34, 2600-2611.

Tompkins, A.M., Bechtold, P., Beljaars, A.C.M., Janiskova, M., Koehler, M., Lopez, P., Morcrette, J. J., (2004), "Moist physical processes in the IFS: progress and plans", ECMWF Technical Memorandum 452, 91.

Uppala, S., Dee, D., Kobayashi, S., Berrishford, P. and Simmons, A., (2008), "Towards a climate data assimilation system: status update of ERA-Interim", ECMWF Newsletter No. 115, pages 12-18. (available at http://www.ecmwf.int).

Venkatachalam, P., Mohan, B.K., Kotwal, A., Mishra, V., Muthuramkrishna, V., and Pandya, M., (2001), "Automatic delineation of watershed for hydrological Application", Paper Presented at the 22nd Asian Conference on Remote Sensing, 5-9 November, 2001. (http://www.crisp.nus.edu.sg/ ~acrs2001/pdf/015venka.pdf, 10/09/2008).

Vogel, R.M., J.R.M. Hosking, C.S. Elphick, D.L. Roberts, and J.M. Reed, (2009), Goodness-of-fit of Probability Distributions for Sightings as Species Approach Extinction, Bulletin of Mathematical Biology, DPO 10.1007/s11538-008-9377-3, 2009.

Wallis, J.R., (1988), "Catastophes, Computing and Containment: Living in Our Restless Habitat," Speculation in Science and Technology, vol.11, no. 4, pp. 295-315.

WARPO, (2008), "Summary of River and Water Bodies Database, National Water Resources Database", Water Resources Planning Organisation (WARPO), (http://www.warpo.gov.bd/NWRD/RivWtr.html, 10/09/2008).

Webster, P.J. and Hoyos, C., (2004), "Prediction of Monsoon Rainfall and River Discharge on 15-30-Day Time Scales" Online Journal of American Meteorological Society, DOI:10.1175/BAMS-85-11-1745.

WMO, (1992), "Simulated Real-Time Intercomparison of Hydrological Models" Operational Hydrology Report. No. 38.

WMO/TD-No.148: (2008), "Guidelines of verification of QPF", World Meteorological Organization, Research Department, Atmospheric Research and Environment Branch, 7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland.

Woods, A., (2006), "Medium-Range Weather Prediction–The European Approach: The story of the ECMWF", Springer , New York, USA, 270 pages, ISBN-10:0-387-26928-2.

Yue, S., Pilon, P., Phinney, B. and Cavadias, G., (2002), "The influence of autocorrelation on the ability to detect trend in hydrological series", Hydrological Processes, 16 (9) (2002), pp. 1807–1829.

APPENDIX 4.1

Equations and purpose of different categorical statistics (dichotomous methods)

Categorical Statistics (Equations)	**Range**	**Perfect Value**	**Purpose**
Accuracy (Fraction Correct): $Accuracy = \frac{Hits + CorrectNegatives}{Total}$ (4.1.1)	0 to 1.00	1.00	Assessment of intuitiveness
Bias Score (frequency bias): $BIAS = \frac{Hits + FalseAlarms}{Hits + Misses}$ (4.1.2)	0 to Infinity	1.00	Tendency of Under-estimation/forecastin g or over estimation/ forecasting
Probability of Detection (hit rate): $POD = \frac{Hits}{Hits + Misses}$ (4.1.3)	0 to 1.00	1.00	Measures successful estimate/forecast of events
False Alarm Ratio: $FAR = \frac{FalseAlarms}{Hits + FalseAlarms}$ (4.1.4)	0 to 1.00	1.00	Measures unsuccessful estimate/forecast of events
Probability of False Detection (false alarm rate): $POFD = \frac{FalseAlarms}{CorrectNegatives + FalseAlarms}$ (4.1.5)	0 to 1.00	1.00	Assessment of false estimating/forecastin g of events
Threat Score (critical success index): $TS = CSI = \frac{Hits}{Hits + Misses + FalseAlarms}$ (4.1.6)	0 to 1.00	1.00	Assess the correct estimating/forecastin g of events
Odds Ratio: $OR = \frac{Hits * CorrectNegatives}{Misses * FalseAlarms} = \frac{\left(\frac{POD}{1-POD}\right)}{\left(\frac{POFD}{1-POFD}\right)}$ (4.1.7)	(-)Infinity to infinity	0.00	Measures the ratio of the odds of making a hit to the odds of making a false alarm and its logarithm represents probability

APPENDIX 4.2

Equations and purpose of different categorical statistics (continuous variables measures methods)

Equations Statistical Scores	Range	Perfect Value	Purpose
MeanError/ME (additive bias): $= \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)$ (4.2.1)	(-)infinity to infinity	0.00	Measures the average error
(Multiplicative) Bias : $= \frac{\frac{1}{N}\sum_{i=1}^{N} F_i}{\frac{1}{N}\sum_{i=1}^{N} O_i}$ (4.2.3)	(-)infinity to infinity	1.00	Does not measure the magnitude of the errors and correspondence between estimate/forecasts and observations
Correlation Coefficient: $r = \frac{\sum(F-\bar{F})(O-\bar{O})}{\sqrt{\sum(F-\bar{F})^2}\sqrt{\sum(O-\bar{O})^2}}$ (4.2.4)	-1.00 to 1.00	1.00	Good measure of linear association or phase error
Skill Score: $SS = \frac{score_{forecast} - score_{reference}}{score_{perfectforecast} - score_{reference}}$ (4.2.5) Where $score_{forecast}$ = MSE of forecasted data $score_{reference}$ = MSE of observed data	0.00 to 1.00	1.00	Implies information about value of estimate/forecast relative to an alternative (reference) estimate/forecast

APPENDIX 5.1

Summary of nos. of missing rainfall data for July, September and August from 1996 to 2008

July

July	Number of missing data in different years for the month of July												
Year / Stations	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Saidpur	0	0	0	0	0	0	0	0	0	0	0	**31**	0
Rangpur	**31**	**16**	**31**	0	6	**31**	0	0	0	0	0	0	**31**
Pirganj	0	0	**31**	**31**	**31**	0	**31**	0	0	0	0	0	**31**
Phulbari	0	0	0	**31**	**31**	**31**	0	0	0	0	0	0	0
Nawabgonj	**31**	0	0	0	**31**	**31**	**31**	0	0	0	0	0	0
Mahipur	0	**31**	0	**31**	**31**	**31**	0	0	0	0	0	0	**31**
Mithapiukur	0	**31**	0	0	**31**	**31**	0	0	0	0	0	0	0
Kaliganj	0	**31**	0	0	0	0	0	0	0	0	0	0	**31**
Ghoraghat	0	**31**	0	0	0	**31**	0	0	0	0	0	0	0
Debiganj	0	**31**	**31**	0	**31**	**31**	**31**	**31**	0	0	**31**	0	**31**
Badarganj	0	**14**	0	0	**31**	0	**31**	0	0	0	0	0	0
Dimla	0	**14**	0	0	**31**	**31**	**31**	0	0	0	0	0	0
Gaibandha	0	**14**	**31**	**31**	0	**31**	0	**31**	0	0	0	0	0
Gobindagonj	0	**31**	0	**31**	0	**31**	**31**	0	0	0	**31**	0	0
Nilphamari	0	**16**	**31**	**31**	**31**	0	0	0	0	0	0	0	0

August

August	Number of missing data in different years for the month of August												
Saidpur	0	0	0	0	0	0	31	0	0	0	0	0	0
Rangpur	**31**	0	**31**	0	**12**	**31**	**31**	0	0	0	0	0	**31**
Pirganj	0	0	**31**	0	**31**	0	**31**	0	0	0	0	0	**31**
Phulbari	0	0	0	**31**	**31**	**31**	0	0	0	0	0	0	0
Nawabgonj	**31**	**31**	0	0	**31**	**31**	**31**	**31**	0	0	0	0	**31**
Mahipur	0	0	0	0	**31**	0	0	**1**	0	0	0	0	**31**
Mithapiukur	0	0	0	0	**31**	**31**	**31**	0	0	0	0	0	**31**
Kaliganj	0	0	0	0	0	**31**	0	0	0	0	0	0	**31**
Ghoraghat	0	0	0	0	0	**31**	0	0	0	0	0	0	**31**
Debiganj	0	**31**	**31**	0	**31**	0	**31**	0	0	0	0	0	**31**
Badarganj	0	0	0	0	**31**	0	**31**	0	0	0	0	0	0
Dimla	0	**31**	0	0	**31**	0	**31**	0	0	0	0	0	**31**
Gaibandha	0	**31**	0	**31**	0	0	0	0	0	0	0	0	0
Gobindagonj	0	0	0	**31**	0	**31**	**31**	0	0	0	**31**	0	0
Nilphamari	0	**31**	**31**	0	**31**	**1**	0	0	**1**	0	0	**31**	**31**

September

September	Number of missing data in different years for the month of September												
Year / Stations	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Saidpur	0	0	0	0	0	0	0	0	0	0	0	**30**	**30**
Rangpur	**30**	0	**30**	0	**8**	0	**30**	0	0	0	0	0	**30**
Pirganj	0	0	**30**	0	**30**	0	0	0	0	0	0	0	**30**
Phulbari	0	0	0	**30**	**30**	0	0	0	**30**	0	0	0	0
Nawabgonj	**30**	**30**	0	0	**30**	0	**30**	0	**30**	0	0	0	0
Mahipur	0	0	0	0	**30**	0	0	**30**	0	0	0	**30**	**30**
Mithapiukur	0	0	0	0	**30**	0	0	0	0	0	0	0	**30**
Kaliganj	0	0	0	0	0	0	0	0	0	0	0	0	**30**
Ghoraghat	0	0	0	0	0	0	0	0	**30**	0	0	0	0
Debiganj	0	**30**	0	0	**30**	0	**30**	0	0	0	0	0	**30**
Badarganj	0	0	0	0	**30**	0	**30**	0	0	0	0	0	**30**
Dimla	0	**30**	0	0	**30**	0	0	0	0	0	**30**	0	**30**
Gaibandha	0	**30**	0	0	0	0	0	0	0	0	0	0	**30**
Gobindagonj	0	0	0	**30**	0	0	**30**	0	0	0	**30**	0	**30**
Nilphamari	0	**30**	**30**	0	**30**	0	0	0	0	0	0	0	**30**

APPENDIX 5.2

Base groups of rainfall stations

Sl. No.	Base Stations (Long period mean rainfall in mm)	Neighboring or Surrounding Stations (Long period mean rainfall in mm)
01	Kaliganj (7.00)	Mahipur (6.42), Dimla (7.94), Debiganj (6.93), Nilphamari (5.65)
02	Nilphamari (5.65)	Saidpur (5.89), Mahipur (6.42), Kaliganj (7.00), Debiganj (6.93 (NRM)
03	Mahipur (6.42)	Saidpur (5.89), Rangpur (6.12), Badarganj (5.56), Nilphamari (5.65) (NRM)
04	Saidpur (5.89)	Pirganj (6.00), Mahipur (6.42), Badarganj (5.56), Nilphamari (5.56) (AM)
05	Pirganj (6.00)	Saidpur (5.89), Phulbari (5.22), Badarganj (5.56) (NR)
06	Badarganj (5.56)	Saidpur (5.89), Pirganj (6.00), Phulbari (5.22), Nawabgonj (5.39), Mahipur (6.42), Mithapiukur (5.65), Rangpur (6.12)
07	Mithapiukur (5.65)	Rangpur (6.12, Nawabgonj (5.39), Badarganj (5.56), Gaibandha (5.46)
08	Nawabgonj (5.39)	Phulbari (5.22), Mithapiukur (5.65), Ghoraghat (6.67), Gaibandha (5.46)
09	Phulbari (5.22)	Pirganj (6.00), Nawabgonj (5.39), Badarganj (5.56)
10	Ghoraghat (6.67)	Nawabgonj (5.39), Gaibandha (5.46), Gobindagonj (4.7)
11	Rangpur (6.12)	Mahipur (6.42), Mithapiukur (5.65), Badarganj (5.56)
12	Dimla (7.94)	Debiganj (6.93) and Kaliganj (7.00)
13	Gobindagonj(4.7)	Ghoraghat (6.67), Gaibandha (5.46)
14	Gaibandha (5.46)	Nawabgonj(5.39), Mithapiukur (5.65), Ghoraghat (6.67), Gobindagonj (4.7)
12	Debiganj (6.93)	Kaliganj (7.00), Dimla (7.94), Nilphamari (5.56)

APPENDIX 5.3

Selection of method of missing data generation using relative bias analysis

Sl No	*Base Staions (Mean Rainfall in mm of 30 years data)*	Relative Bias in percentage (%) for different methods			Selection of method of missing data treatment
		Arithmetic Mean	Normal Ratio Method	Inverse Distance Power Method	
01	Kaliganj (7.00)	2.20	0.65	5.73	Normal Ratio Method (NRM)
02	Nilphamari (5.65)	41.96	4.65	24.08	Normal Ratio Method (NRM)
03	Mahipur (6.42)	45.29	34.98	35.53	Normal Ratio Method (NRM)
04	Saidpur (5.89)	17.69	28.35	24.40	Arithmetic Mean (AM)
05	Pirganj (6.00)	37.55	14.25	65.93	Normal Ratio Method (NRM)
06	Badarganj (5.56)	8.25	46.30	48.21	Arithmetic Mean (AM)
07	Mithapiukur (5.65)	21.37	32.19	31.63	Arithmetic Mean (AM)
08	Nawabgonj (5.39)	24.31	14.38	11.60	Inverse Distance weighted (IDW)
09	Phulbari (5.22)	56.35	29.31	42.75	Normal Ratio Method (NRM)
10	Ghoraghat (6.67)	50.32	15.54	45.09	Normal Ratio Method (NRM)
11	Rangpur (6.12)	12.27	10.81	15.08	Normal Ratio Method (NRM)
12	Dimla (7.94)	24.92	16.31	36.81	Normal Ratio Method (NRM)
13	Gobindagonj(4.7)	52.44	18.51	20.20	Normal Ratio Method (NRM)
14	Gaibandha (5.46)	48.49	47.42	50.54	Normal Ratio Method (NRM)
15	Debiganj (6.93)	4.79	2.05	6.44	Normal Ratio Method (NRM)

Goodness of fit tests

a) Chi-square Test

The *Chi-Square Statistic* is calculated (Chow et al, 1988) by the equation (6.1.1) given below:

$$\chi^2_{computed} = \sum_{j=1}^{m} \frac{\left(O_j - E_j\right)^2}{E_j} \qquad (6.1.1)$$

Where, m is the number of class intervals; O_j is an observed frequency in interval j, N is the sample size and E_j is an expected frequency given by equation (6.1.2) below,

$$E_j = \frac{N}{m} \qquad (6.1.2)$$

The Chi-square critical is obtained from statistic table as

$$\chi^2_{critical} = X^2_{(1-\alpha),(m-p-1)} \qquad (6.1.3)$$

Where, (m-p-1) is the degree of freedom; p is the number of parameters used in fitting the proposed distribution; (1-α) is the confidence level chosen for the test.

b) Kolmogorov-Smirnov (K-S)

Kolmogorov-Smirnov (Kolmogorov, 1933) test test is given by the equation (6.1.4):

$$D = Max\left(F_N(x) - F_O(x)\right) \qquad (6.1.4)$$

Where, $F_N(x)$ is estimated as N_j / N. Where N_j is the cumulative number of sample events at class limit *j*. $F_o(x)$ is then 1/k, 2/k …etc., where k is the number of class intervals. Class limits are obtained the same way as in the chi –square test (Rao and Hamed, 2000). The critical value of K-S test, d_α, at 5 % significance level is given by:

$$d_\alpha = \frac{1.36}{\sqrt{N}} \qquad (6.1.5)$$

With N, the sample size. If D < d_α, then the distribution is fitting (Hogg and Tannis, 1988).

c) D-index Test

The *D-index test* (Cohen, 1977 and 1988) is given by the following equation:

$$D - Index = \frac{1}{\bar{x}} \sum_{i=1}^{6} |x_i - \hat{x}_i| \quad (6.1.6)$$

Where: $\bar{x}$ = mean of the observed series, $x_i = i^{th}$ highest observed value for the distribution arranged in descending order; $\hat{x}_i = i^{th}$ Computed value for the distribution. For computing the value of D-index, the highest six observations are used. The distribution, which gives the minimum D-Index, was considered as the best fit distribution.

d) L-moment-ratio

Sample probability weighted moments are given below:

$$b_0 = \frac{1}{n} \sum_{j=1}^{n} x_j \quad (6.1.7)$$

$$b_1 = \frac{1}{n} \sum_{j=2}^{n} \frac{(j-1)}{(n-1)} x_j \quad (6.1.8)$$

$$b_2 = \frac{1}{n} \sum_{j=3}^{n} \frac{(j-1)(j-2)}{(n-1)(n-2)} x_j \quad (6.1.9)$$

$$b_r = \frac{1}{n} \sum_{j=r+1}^{n} \frac{(j-1)(j-2)...(j-r)}{(n-1)(n-2)...(n-r)} x_j \quad (6.1.10)$$

Where, n is the sample size and x_j is the j^{th} element in ascending order.

L-moment is based on the linear combinations of probability weighted moments and 'L' signifies the linearity. The first 'L' moment refers the location and is known as L-mean (l_1). The second 'L' moment is a measure of scale and dispersion and termed as L- scale (l_2). The third and fourth 'L' moments are measure of symmetry and peakedness respectively (l_3 & l_4). The first few *L*-moments are defined by

$$l_1 = b_0 \quad (6.1.11)$$

$$l_2 = 2b_1 - b_0 \quad (6.1.1)$$

$$l_3 = 6b_2 - 6b_1 + b_0 \tag{6.1.13}$$

$$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \tag{6.1.14}$$

L-moment ratios, dimensionless quantities and independent of the units of measurement of the data, can be obtained by dividing the higher-order *L*-moments by the dispersion measure and defined by Hosking (1990) as,

L-moment ratios	Expressions	Range of values
L- Cv	$t_2 = \frac{l_2}{l_1}$	$0 \le t_2 < 1$
L-skewness	$t_3 = \frac{l_3}{l_2}$	$-1 \le t_3 \le 1$
L- kurtosis	$t_4 = \frac{l_4}{l_2}$	$-1 \le t_4 \le 1$

LIST OF PUBLICATIONS

1. Rahman, M.M., Arya, D.S., Goel, N.K. and Dhamy, A.P., (2010), "Design Flow and Stage Computations in the Teesta River, Bangladesh using Frequency Analysis and MIKE 11 Modeling", Journal of Hydrologic Engineering, DOI:10.1061/(ASCE) HE1943-5584.0000299. (In press). Submitted 6 July 2009; accepted 21 July 2010.

2. Rahman, M. M, Arya, D.S. and Goel. N.K., (2009), "Limitation of 90 m SRTM DEM in drainage network delineation using D8 method—a case study in flat terrain of Bangladesh", Applied Geometrics Journal, Volume 2, Number 2, 49-58, DOI: 10.1007 /s12518-010-0020-2, Springer Link publishers. Submitted: 4 April 2009 / Accepted: 8 March 2010.

3. Rahman, M. M, Arya, D.S., Goel. N.K. and Mitra, A.K. (2010), "Rainfall statistics evaluation of ECMWF and TRMM rainfall data for flood studies – A Case Study in Ganges–Brahmaputra-Megna Basin" (Recommended with revision for publication in Journal of "Meteorological Applications", Wiley InterScience), Submission No. Manuscript ID: MET-10-0050.R1, Submitted on: 20/04/2010.

4. Rahman, M. M., Goel. N.K. and Arya, D.S., (2010), "Advancement of Flood Forecasting and Warning System in Bangladesh for Risk Management - Present and Future", Pubished in the proceedings of the the 3rd International ASCE Conference on Current & Future State of Water Resources and Environment (EWRI-IITM 2010).

5. Goel. N.K., (2010), Rahman, M. M, and Arya, D.S., "Recent Advances in Early Flood Warning Systems - A Conceptual Framework for Jamuneshwari River Basin, Bangladesh", Accepted for the 4th International Perspective on Water Resources and the Environment (IPWE 2011), ASCE Conference in Singapore, Submission ID. IPWEA 00162-00637.

6. Rahman, M. M., Arya, D.S. and Goel. N.K., (2008), "Approach of Early Flood Warning System for Urban Flood Risk Mitigation", Published in the proceedings of International Conference on Disaster and Development –Bridging the gap between theory and practice (IC0DAD 2008), Kathmandu, Nepal.

7. Kabuya, P.M., Rahman, M. M., Arya, D.S., and Goel. N.K., (2010), "Prediction and Mapping of Extreme Rainfall Quantiles by Stochastic and GIS Approach in North West of Bangladesh" (communicated to J. of "Water Resources Management", Springer Link Publishers), Submission No. WRM-S-10-00314 Submitted on: 14/05/2010.

8. Arya, D. S., Kabuya, P. M., Rahman, M.M. and N. K. Goel, (2010), "Projection of Climate Change Impact on Flooding in Bangladesh", Accepted in the 4th International Perspective on Water Resources and the Environment (IPWE 2011), ASCE Conference in Singapore, Submission ID. IPWEA00392-00637.